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Surface Wave Dispersion Measurements and Tomography from Ambient Seismic Noise in India, W. China, and Pakistan

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1. Executive Summary

The proposed research is in response to the NNSA/AFRL/SMDC Broad Agency Announcement for Fiscal Year 2007 regarding nuclear monitoring research and engineering (Solicitation Number DE-SC52-06NA27305). The proposal responds particularly to Research Topic 2, *Seismic Calibration and Ground Truth Collection*.

The "path calibration problem" for surface waves is defined by the need to reliably detect and extract small amplitude surface wave packets so that spectral amplitude measurements can be obtained. The regional application of the $M_s : m_b$ discriminant requires measurement of M_s at periods of 8 - 12 sec, so accurate prediction of surface wave arrival times at these periods is needed. The CU-Boulder group has developed a promising new approach to surface wave path calibration based on the use of long records of ambient seismic noise. The proposed work will apply this method, which we call ambient noise tomography, to the significant data resources that are now available and are continuing to emerge in India and W. China. Ambient noise surface wave path calibration promises to produce better information at short periods, in aseismic regions, and with meaningful uncertainty estimates than produced from traditional earthquake-based surface wave methods. The application of the method to open source data from the FDSN and IRIS PASSCAL experiments and to proprietary data from Indian collaborators at the National Geophysical Research Institute in Hyderabad, India will produce unsurpassed path distribution and density across much of India, W. China, and N. Pakistan.

There are four principal deliverables: (1) the new data set of ambient noise based inter-station estimated Green functions, (2) the group velocity measurements and associated uncertainties from 6 sec to 30 sec period, (3) new group velocity tomographic maps from 8 sec to 30 sec period, and (4) the reports and publications documenting the application of ambient noise tomography to the study region.

2. Proposal Narrative

2.1 Overview and Mission Relevance

The proposed research is in response to the NNSA/AFRL/SMDC Broad Agency Announcement for Fiscal Year 2007 regarding nuclear monitoring research and engineering (Solicitation Number DE-SC52-06NA27305). This proposal particularly responds to Research Topic 2, *Seismic Calibration and Ground Truth Collection*. There is also overlap with Research Topic 3, particularly on Velocity Models. This proposal will apply a new method for short period surface wave path calibration India, western and central China, and northern Pakistan.

Detection, location, and identification of nuclear explosions by the Air Force Technical Application Center (AFTAC) depend upon calibration of source and path effects to ensure maximum efficiency to monitor at small magnitudes. The $M_s : m_b$ discriminant and its regional variants are the most reliable transportable means of discriminating earthquakes from explosions (e.g., Stevens and Day, 1985; Levshin and Ritzwoller, 2001b). To measure surface wave amplitudes accurately in order to estimate M_s is very challenging for small magnitude events in which surface waves may not be readily identifiable in raw seismograms. Because amplitude spectra of regionally recorded small magnitude events typically peak below 20 sec period (where M_s is usually measured), the regional application of the $M_s : m_b$ discriminant can be significantly improved when M_s is measured at shorter periods; i.e., 8-12 s period (e.g., Levshin and Ritzwoller., 2001a). To provide these amplitude measurements, it is crucial to be able to reliably detect and extract small amplitude surface wave packets so that spectral amplitude measurements can be obtained. To succeed in both of these efforts requires the ability to predict the group dispersion curves for all source-station paths of interest. We refer to this as the "path calibration problem" for surface waves.

Under existing funding from DoE/NNSA (DE-FC52-2005NA26607), we have developed a new method to approach the path calibration problem based on the use of long records of ambient seismic noise. To develop the method, we have begun to apply it to the large broadband data set that has emerged through the growing Virtual European Broadband Seismic Network (VEBSN). This method, which we call "ambient noise tomography", is based on the ability to estimate surface-wave Green functions by cross-correlating long sequences of ambient seismic noise (Shapiro and Campillo 2004; Shapiro et al., 2005). Dispersion measurements made on the estimated Green functions present significant advantages over traditional measurements made on recordings of waves emanated from earthquakes. Ambient noise tomography is particularly useful in calibrating surface-wave path effects in aseismic regions and at periods below 20 sec.

The proposed work will apply the ambient noise tomography method to the significant data resources that are now available and emerging in India and W. China. These resources include data from the permanent Federation of Digital Seismographic Network (FDSN),

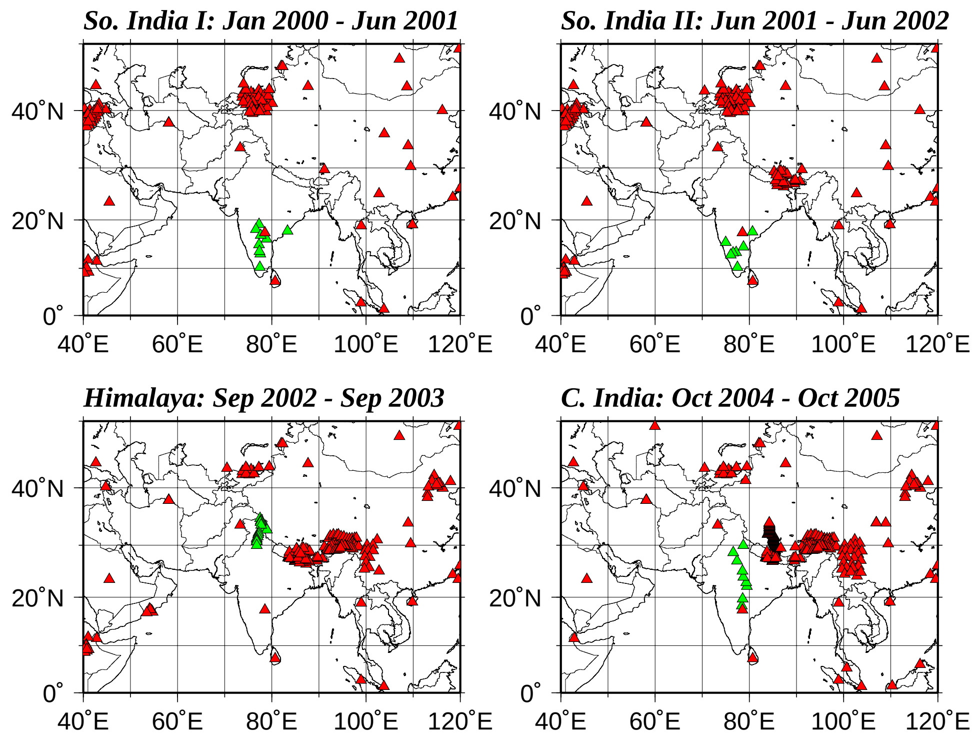

Figure 1: **Station coverage during each of the deployments of the NGRI experiments.** Red triangles – FDSN and PASSCAL data available from the IRIS DMC. Green triangles – NGRI deployments.

temporary US PASSCAL installations in and around China, and temporary broad-band deployments in India. The volume of PASSCAL data that are available, in particular, will grow appreciably during the contract period. Data from our Indian collaborators at the National Geophysical Research Institute (NGRI) in Hyderabad (Shyam Rai) will be the focal point for much of the proposed research. These data provide unique paths through India and W. China. The locations of most of the stations to be used in this study are shown in Figure 1. These maps are segregated by time period according to the location of the Indian stations. The combined station set is much larger and better distributed than that employed in earlier tomographic studies in C. Asia. The region of study includes W. China, most of India, and parts of N. Pakistan, all current nuclear states.

The proposed research should be understood in light of the two main approaches to the path calibration problem that are used in nuclear monitoring. These approaches depend on the nature of the information used to predict the dispersion curves: (1) empirical path calibration (e.g., Patton and Jones, 1998) and (2) tomography-based path calibration (e.g., Levshin and Ritzwoller, 2001a). In empirical path calibration, dispersion measurements are obtained at the monitoring stations for a set of well located events in the region of study. In tomographic calibration, dispersion measurements are obtained at the monitoring

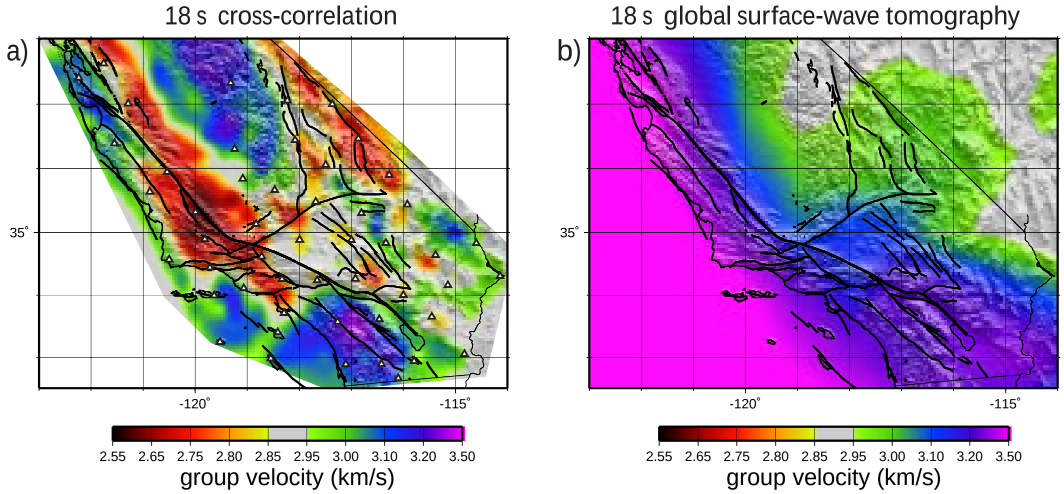

Figure 2: **Ambient noise tomography compared with traditional global teleseismic earthquake tomography across Southern California.** (a) The 18 sec group speed map on a 0.25 degree grid derived from group speeds measured on cross-correlations between 62 USARRAY Transportable Array stations (Shapiro et al., 2005a). (b) The 18 sec group speed map derived from global earthquake teleseismic tomography, presented for comparison (Ritzwoller et al., 2002). Ambient noise tomography provides much better lateral resolution than traditional earthquake tomography, particularly in the context of a regional array.

stations and other relevant stations for events potentially distributed over an area much larger than the region of interest. Tomographic calibration methods are used to construct period-dependent maps of local surface wave velocities that are then converted into dispersion curves for individual paths using ray-tracing. Both approaches have their strengths and weaknesses and it has been suggested that an optimal solution to the path calibration problem would combine empirical information for paths where direct measurements are available with tomographically predicted travel times elsewhere.

The proposed research will contribute unique information to both empirical and tomographic surface wave path calibrations in the study region. (1) New empirical information will include the estimated surface wave Green functions themselves and the dispersion measurements obtained on them between station-pairs. Many earthquake-station paths have been empirically calibrated in Central Asia, but station-station paths have never before been calibrated empirically. (2) Tomography-based calibration in Central Asia will be improved due to the unique capabilities offered by ambient noise tomography. In particular, ambient noise tomography has been shown to deliver better short period dispersion information (5 - 15 sec period) with better lateral resolution than traditional earthquake-based tomography. Figure 2 gives an example.

In the context of nuclear monitoring, short period surface wave dispersion information is very hard to obtain. Information from 5 - 15 sec period that emerges naturally from ambient noise tomography provides a great improvement over traditional earthquake-based surface wave studies. Short period information emerges strongly from the ambient noise method because the band from 5 - 15 sec is the microseism band where ambient noise is very strong. In contrast, short period surface waves that propagate from earthquakes, particularly at teleseismic distances, are more strongly scattered and attenuated than at longer periods, making dispersion below 15 sec period generally difficult to measure.

2.2 Results of Previous Work

2.2.1 Development of Ambient Noise Tomography

2.2.1a Background

Background seismic noise is excited by spatially and temporally distributed natural and artificial sources and, when considered over sufficiently long times, includes surface waves propagating in many directions. It, therefore, contains information about surface wave propagation and consequently the elastic structure of the crust and uppermost mantle. This information can be extracted by computing the two-point cross-correlation between noise records from each station pair. The relationship between the cross-correlation and the Green function of the wave propagating between the pair of stations is well established (e.g., Weaver and Lobkis, 2001; Snieder, 2004). The use of background noise to extract Green functions has been applied successfully in a number of fields, including helioseismology, ultrasonics, exploration seismology, and marine acoustics.

In seismology, two types of signals have been considered to compose random wavefields and utilized to infer Green functions by cross-correlation. The first type of random wavefield is seismic coda, which results from multiple scattering of seismic waves from small-scale inhomogeneities. Campillo and Paul (2003) extracted fundamental-mode Rayleigh and Love waves by correlating coda waves following regional earthquakes in southern Mexico at stations separated by a few tens of kilometers. The second type of wavefield is “ambient” seismic noise excited by superficial sources such as ocean microseisms (e.g., Webb, 1998), infragravity waves (e.g., Rhie and Romanowicz, 2004), and atmospheric disturbances (e.g, Tanimoto, 1999). By correlating vertical records of ambient noise at stations separated from about 100 km to more than 2000 km, Shapiro and Campillo (2004) demonstrated that it is possible to extract fundamental mode Rayleigh waves at periods from about 7 sec to more than 100 sec. Similar proof-of-concept results, predominantly at periods below about 20 sec, have been established by Sabra et al. (2005a). Roux et al. (2005) have shown that at much shorter inter-station paths (several 10s of km) crustal P-waves near 1 Hz can also be extracted from

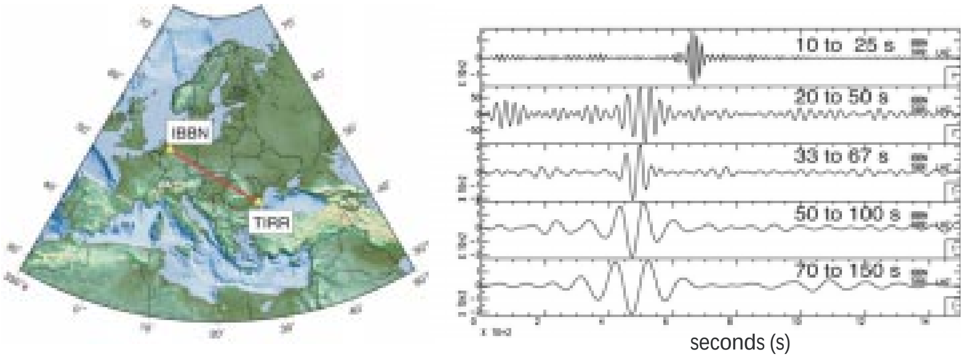

Figure 3: **Example of a broad-band cross-correlation in Europe.** IBBN (Ibbenbueren, Germany) and TIRR (Hungary).

cross-correlations. Ambient noise tomography has been used to produce group velocity maps between 7 and 20 sec period in Southern California by Shapiro et al. (2005) (see Fig. 2) and Sabra et al. (2005b).

2.2.1b Observational Methodology

Under existing funding from DoE/NNSA (DE-FC52-2005NA26607), we have been developing the methods to obtain robust inter-station dispersion curves with reliable uncertainty information. In outline, the process is as follows: (1) data processing including cross-correlation and stacking, (2) dispersion measurement, (3) uncertainty estimation, and (4) tomography.

First, data are processed one day at a time. After removing the mean, daily trend and the instrument response, the data are filtered into several different period bands: e.g., 5-30 sec, 20-50 sec, and 33-100 sec. In each band, the data are whitened in frequency and then amplitude normalized in time to suppress temporally localized events such as earthquakes and automatic mass re-centering. Cross-correlations between stations are then computed daily and stacked into overlapping three month and finally a whole year time series. An example of cross-correlations for a station pair in Europe is shown in Figure 3 and Figure 4 presents an example record-section. The signal-to-noise ratio (SNR) is then computed by comparing the peak amplitude of the signal in the group velocity windows defined by the global model of Shapiro and Ritzwoller (2004) with the root-mean-square noise trailing the arrival window. Bensen et al. (2006) describe this procedure in much greater detail. Conclusions about the existence or absence of coherent noise between pairs of stations are made on the basis of the SNR. SNR often reported is from the "symmetric signal", the average of the cross-correlations with positive and negative lag, so that a single SNR is reported for each station pair.

Second, if the SNR criterion is met, group speed curves are measured in each period

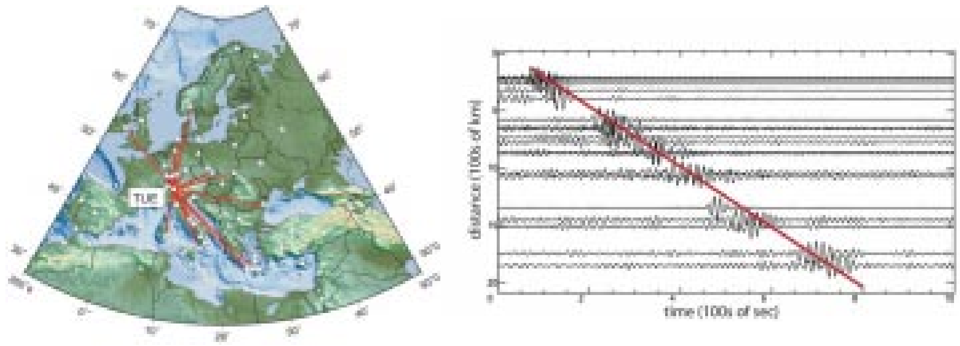

Figure 4: **Example of a cross-correlation record-section in Europe.** Result is centered on station TUE (Stuetta, Italy), for the symmetric-signal, band-pass filtered from 20 - 50 sec, and only high SNR cross-correlations are shown.

band in the three-month and year-long time series. Significant efforts have been devoted to automating this process, as the analyst-driven measurements applied to earthquake are impractical. Automation is the basis for the technique's cost-effectiveness.

Group speed curves are measured automatically for each of the period bands on each three-month and year-long stack. As in earthquake dispersion analysis (e.g., Ritzwoller and Levshin, 1998), automated dispersion measurement is based on Frequency Time Analysis (FTAN) in a two-step process. In the first step, traditional FTAN creates a two-dimensional diagram of power as a function of time and the central frequency of the applied filters (Fig. 5, Middle Row). The automatic procedure traces the local power maxima along the frequency axis. The group times of the maximum amplitude as a function of filter frequency are used to calculate the tentative (raw) group velocity curve. Measures are taken to ensure the continuity of this curve by rejecting jumps in group arrival times. The formal criteria are set to reject curves with distinctly irregular behavior or interpolate through small holes by selecting realistic local instead of absolute maxima. The second part of the method is the application of a phase-matched or anti-dispersion filter (Fig. 5, Bottom Row). In the non-automated method, the analyst defines both the phase-matched filter and the frequency band of the measurement. In the automated method, the frequency band is pre-set and the phase-matched filter is defined by the dispersion curve that results from the first step of the process. Phase-matched filtering collapses the signal into an "delta-like" arrival, ideally. In the traditional analysis, the analyst defines a window to extract this signal which is then re-dispersed and a cleaned FTAN image is returned. The automated procedure is similar, but the windowing and extraction of the signal is done automatically. In both the traditional and automated analyses, the actual frequency of a given filter is found from the phase derivative of the output at the group time of the selected amplitude maximum (Levshin and Ritzwoller, 2001a). Figure 5 shows an example of the measurement procedure. For each station-pair, there are dispersion measurements obtained on the positive and negative lag and the average of the two which we call the "symmetric signal". At present, only the dispersion curve made

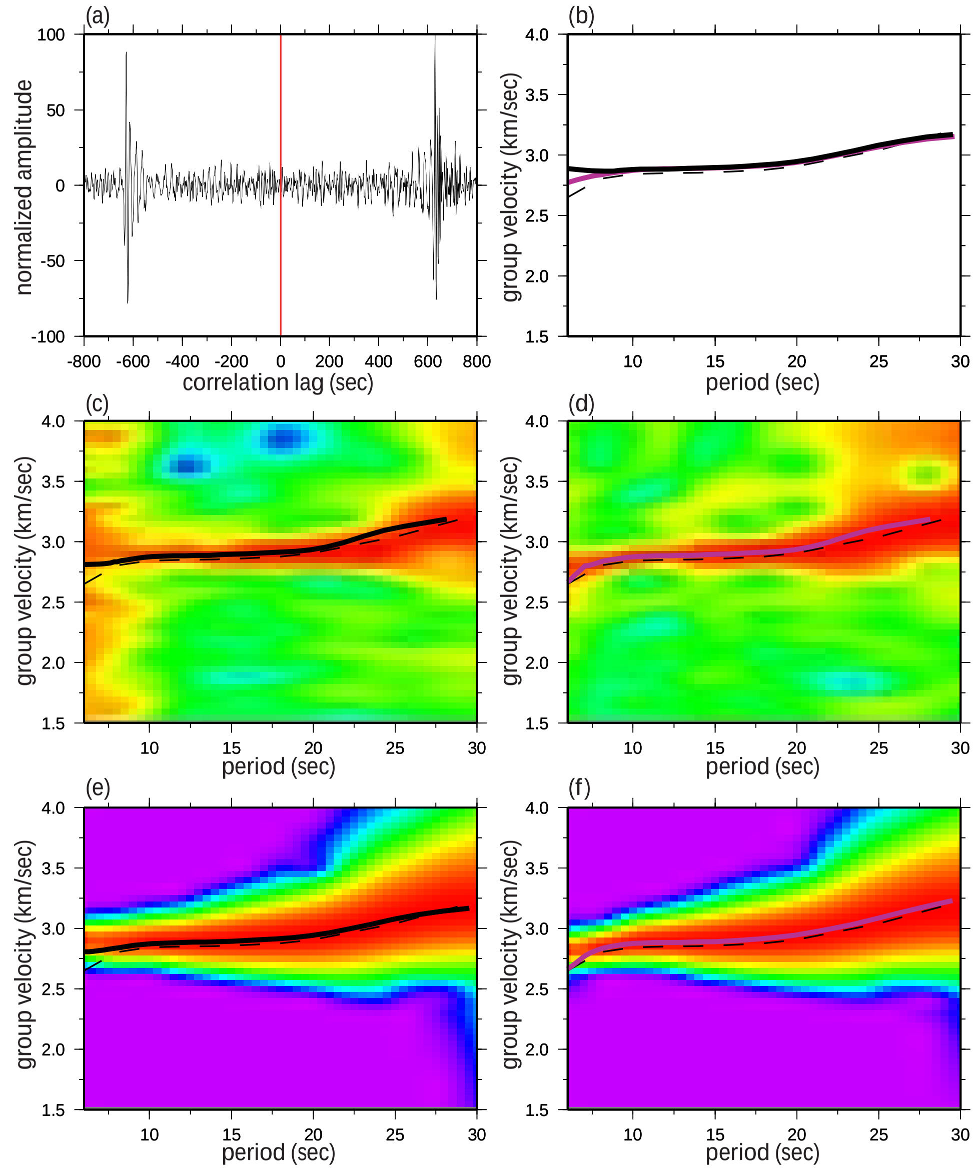

Figure 5: **FTAN and phase-matched filtering.** (TOP LEFT) Cross-correlation obtained between GRFO (Graefenberg, Germany) and OBN (Obninsk, Russia), at 1810 km inter-station distance. (TOP RIGHT) Group speed curves from positive and negative lags using phase matched filtered FTAN diagram, compared with the dashed line, the prediction from the 3-D model of Shapiro and Ritzwoller (2002). (MIDDLE ROW) Raw FTAN diagrams applied to positive and negative lag signals. (BOTTOM ROW) FTAN diagrams after phase-matched filtering.

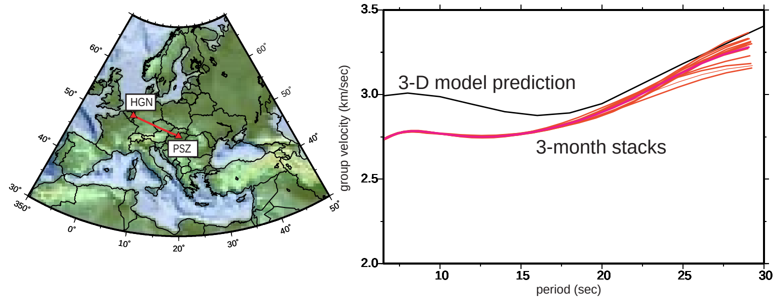

Figure 6: **Dispersion curves and seasonal variability.** Stations are HGN (Heijmans Groeve, Netherlands) and PSZ (Piszkes-teto, Hungary). Red curves are group speed curves obtained on 5 sec to 30 sec band-pass filtered 3-month time series. The black line is the prediction from the 3-D model of Shapiro and Ritzwoller (2002), shown for comparison.

from the symmetric signal are being used in tomography.

Third, one of the great advantages of dispersion measurement from ambient seismic noise is the ability to repeat the measurement for different time periods and use the result to estimate measurement uncertainties. Because ambient noise conditions change seasonally, the similarity of repeated measurements gives us confidence in the veracity of the result. We measure dispersion curves on three-month stacks off-set in time by one month, so that over a year there are 12 resulting dispersion curves. Group speeds obtained from the stacks with SNR>7 are used to define the standard deviation σ of the measurement. The reported dispersion curve is from the 12-month stack. It is retained for tomography if the measurement standard deviation is less than three times the average standard deviation over all measurements. Figure 6 shows an example of seasonal variability and the resulting variation in the observed dispersion curves. The seasonal variability is the basis for uncertainty estimates, which are very low in this example.

Fourth, the final stage of ambient noise tomography is group speed tomography itself. Dispersion measurements between station-pairs can be used to produce group speed maps exactly as earthquake data are used. At present, our maps are based on ray tomography, but spatially extended finite-frequency sensitivity kernels can also be used. Through simulations we have shown that the finite-frequency kernels will be the same as those from earthquakes. Recently, it has been suggested that group delay tomography is ill-posed due to a simultaneous sensitivity to phase speeds (Dahlen and Zhou, 2006), but Barmin et al. (2005) showed that from a practical perspective this is a higher-order effect and can be ignored in group speed tomography, particularly at the short period proposed here.

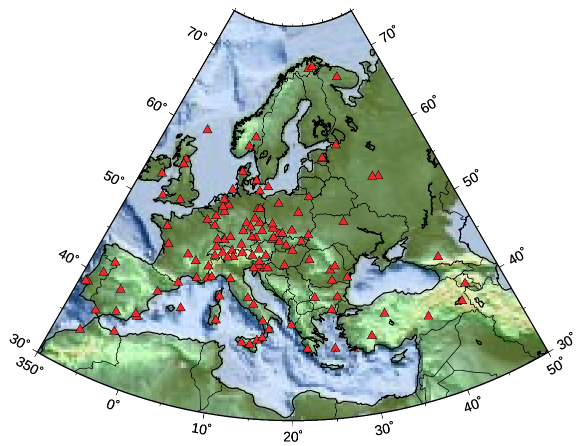

Figure 7: **Stations from the VEBSN.**

2.2.1c Ambient Noise Tomography for Europe

Current funding from DoE/NNSA (DE-FC52-2005NA26607) exists primarily to develop ambient noise tomography for application to nuclear monitoring. As part of this development effort, we have begun to apply the method in Europe because of good station coverage and a priori knowledge of geological structures. These characteristics have allowed us to tune the method for application in regions with fewer data resources or a more poorly understood geological/tectonic setting. Station coverage is currently expanding rapidly in Europe and in the Mediterranean region generally due to the emergence of the Virtual European Broad-Band Seismic Network (VEBSN). The results presented here are for a set of about 125 stations shown in Figure 7.

Figure 8 shows the results of preliminary group speed tomography at 12 sec, 16 sec, and 30 sec period across Europe. Tomography was run on a $1^\circ \times 1^\circ$ grid using 12-month symmetric component cross-correlations. Although there are more than 7000 inter-station paths, after data rejection 1664 paths remain at 12 sec, 3241 paths at 16 sec, and 2450 paths at 30 sec period. The estimated maps are embedded into the group velocity maps predicted from the 3-D model of Shapiro and Ritzwoller (2002) where data coverage is low which occurs mainly near the southern and eastern edges of the maps. The maps possess significantly different sensitivities to earth structure, with the 12 and 16 sec maps being primarily sensitive to sedimentary thicknesses and speeds and the 30 sec map more strongly affected by average crustal wave speeds and thicknesses.

The reliability of the maps can be assessed using several lines of evidence: repeatability of the measurements, agreement with known geological structures, and coherence of the measurements. First, repeatability of the measurements in different seasons is discussed above and is the basis for measurement uncertainty estimates. Measurements are not retained unless they are robust over multiple seasons.

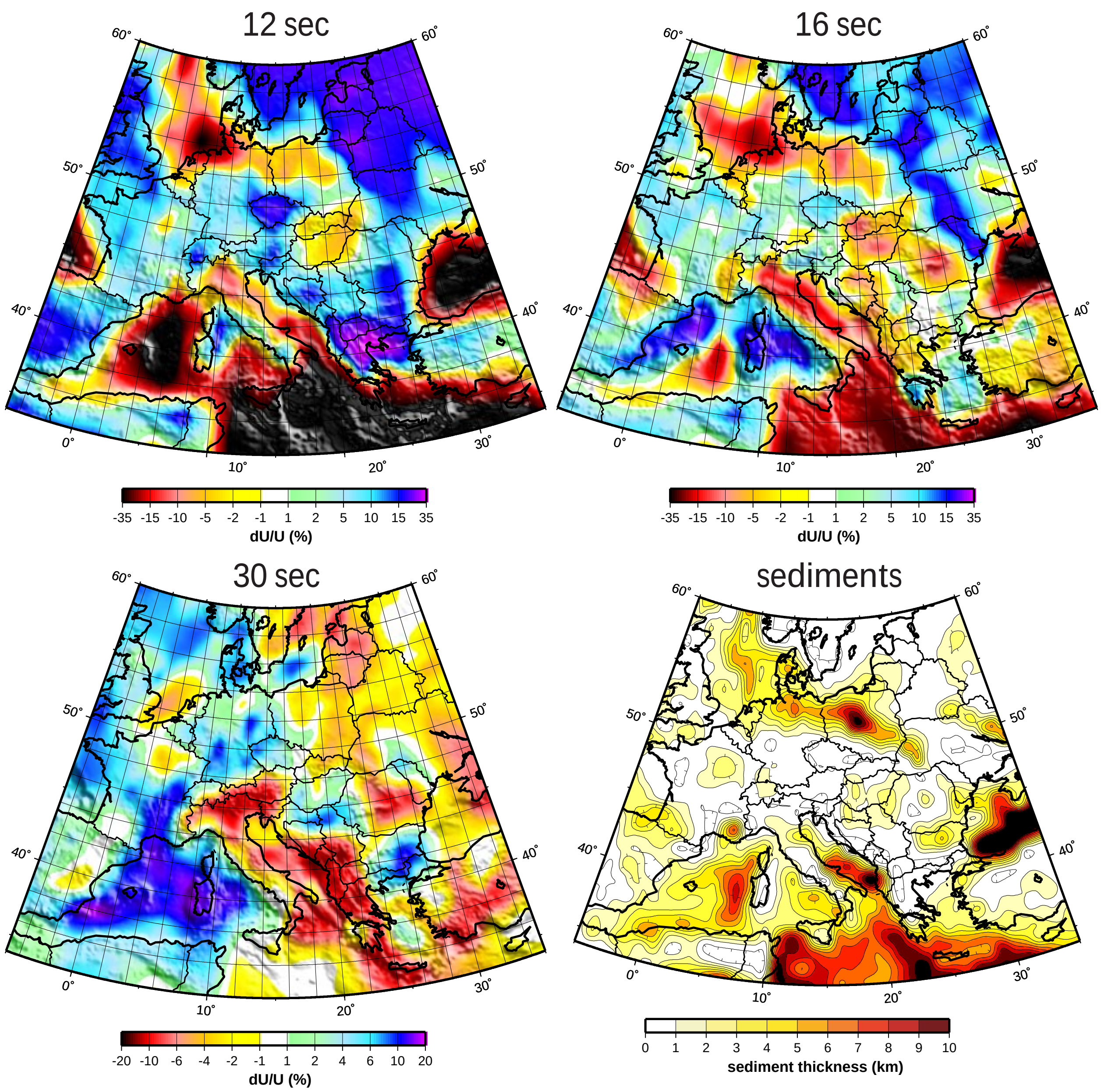

Figure 8: **Ambient noise tomography results in Europe using VEBSN data.** Sedimentary thicknesses are shown for comparison with the 12 sec and 16 sec maps.

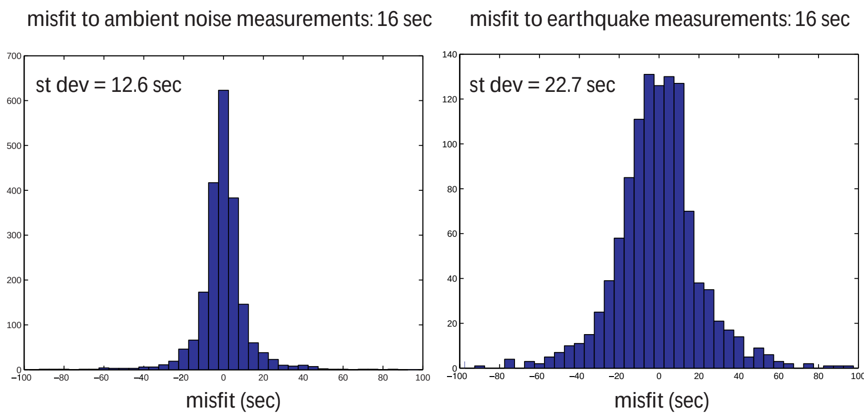

Figure 9: **Histograms of misfit at 16 sec period.** (LEFT) Misfit to ambient noise group speed measurements across Europe from ambient noise tomography. (RIGHT) Misfit to earthquake group speed measurements across Europe from earthquake tomography.

Second, agreement with known structures, particularly sedimentary basins, is needed. Figure 8 also shows a map of sedimentary thickness from CRUST1.0 which Laske and Masters digitized across most of Europe from the EXXON Tectonic Map of the World (http://mahi.ucsd.edu/Gabi/sediment.html). Many of the basins across Europe are reflected in the 12 sec and 16 sec maps including the N. Sea Basin, the Silesian Basin (N. Germany, Poland), the Panonian Basin (Hungary, Slovakia), the Po Basin (N. Italy, the Rhone Basin (S. France), the Paris Basin, and the basins of the Adriatic and Mediterranean Seas. It is interesting that the expression of the Panonian Basin is stronger in the 16 sec map than expected using the EXXON sedimentary characterization. The 30 sec map should be approximately related to crustal thickness across much of Europe. Low velocities associated with the Alps, mountains in the Balkans, and the Carpathians are probably caused by crustal roots. The general reduction in 30 sec Rayleigh wave speeds in the eastern part of the map is probably related to the general thickening of the crust to the east. Detailed interpretation is beyond the scope of this work, and awaits complementary research which will include inversion for the V_s structure of the crust and uppermost mantle.

Finally, the "coherence" of the measurements relates to the mutual agreement of measurements taken between different stations that span similar paths. This can be determined from the ability to fit the data using smooth tomographic maps such as those in Figure 8, particularly as that fit compares to the fit achieved with earthquake data. Figure 9 plots histograms of misfit using ambient noise and our earthquake data in Europe. The ambient noise data tends to be fit better, partially due to the fact that the earthquake data possess sensitivity to uncertainties in source characteristics. Figure 10 summarizes the standard deviation of misfit after tomography from earthquake and ambient noise data across Europe. As periods reduce below 30 sec, relative misfit of ambient noise improves particularly below about 15 sec period. Generally, we believe short period measurements (< 20 sec) obtained

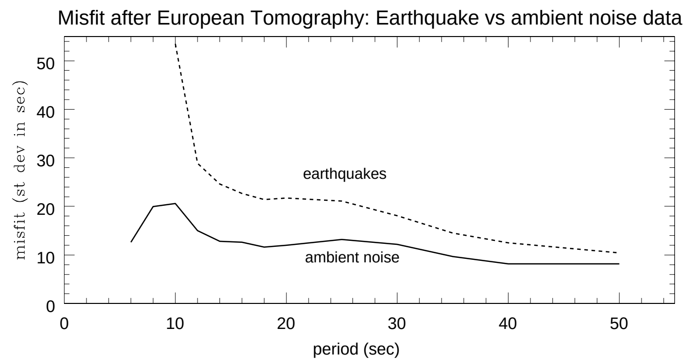

Figure 10: **Summary misfit versus period: Earthquakes versus ambient noise data.**

from ambient noise are preferable to earthquake measurements as discussed above.

2.2.2 Previous Earthquake Group Speed Tomography in Central Asia

We have devoted substantial efforts under previous DoE/NNSA and Air Force support toward developing Rayleigh and Love wave group speed data sets and tomographic maps at short and intermediate periods across Central Asia from earthquake data. These data sets have been widely distributed and used by the US nuclear monitoring community. An example of a group velocity map across much of Central Asia that emerged from our earlier research is shown in Figure 11 for the 15 sec Rayleigh wave.

Due to its substantial intra-continental seismicity, which results from the continental collision between India and Asia, Central Asia is particularly suited for classical earthquake surface wave tomography (e.g., Ritzwoller and Levshin, 1998; Ritzwoller et al., 1998). Nevertheless, at periods below about 15 sec, path coverage is suboptimal, geographically variable, and the quality of the dispersion measurements degrades appreciably compared with longer periods. Resolution estimates from our earthquake data set are shown in Figure 12. Resolution across much of Central Asia from earthquake tomography is fairly good and uniform at periods above about 15 sec, but below that period resolution degrades rapidly, as the 8 sec resolution map shows.

Ambient noise tomography is promising as a method to improve coverage and resolution below 15 sec period across much of Central Asia. The lack of permanent stations within India, however, makes the application of inter-station cross-correlation unsuitable for the sub-continent. The NGRI data, which is the focal point of the proposed research, changes this situation completely as discussed below under Proposed Work.

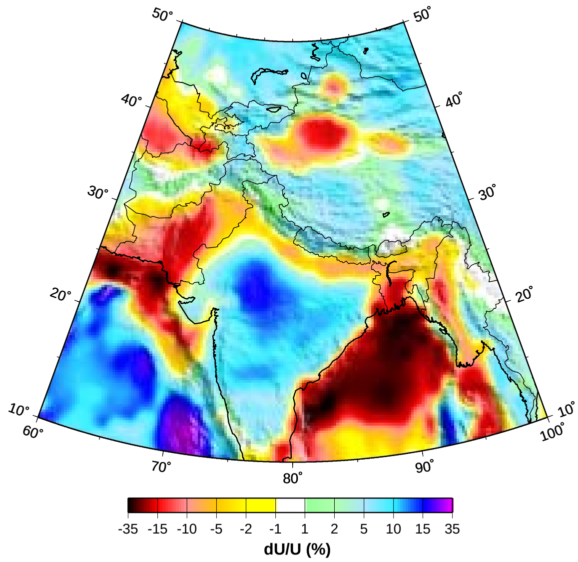

Figure 11: **Group speed map at 15 sec period determined from earlier earthquake tomography in the region of study.**

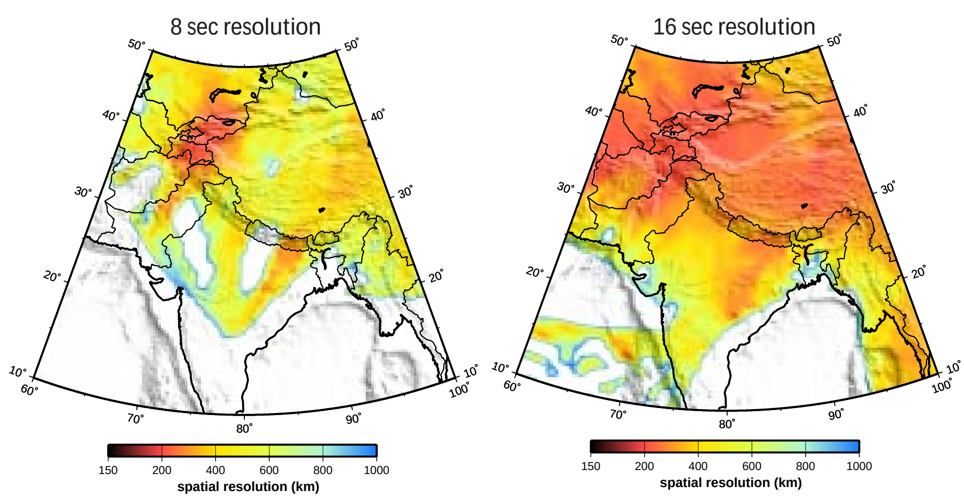

Figure 12: **Resolution from earthquake tomography in the region of study.** Reported resolution is 2σ, where σ is the standard deviation of a Gaussian fit to the resolution surface at each point. Red regions are well resolved, white regions have no resolution.

2.3 Proposed Work

The proposed work divides into three principal units that can be pursued nearly sequentially: (1) acquisition and processing of the data, (2) tomography to produce Rayleigh wave group speed maps from 6 to 30 sec period, and (3) documentation and delivery of data products. Each unit will be discussed in turn.

2.3.1 Data Acquisition and Processing

The data acquisition effort will focus on the use of proprietary data that is being supplied for this research by Dr. Shyam Rai of the National Geophysical Research Institute (NGRI) in Hyderabad, India. There are a total of 45 sites that were occupied by broad-band instruments from the beginning of 2000 through late 2005. The locations of the instruments are shown in Figures 1 and 13. Between 7 - 10 instruments are deployed at a time in five experiments. The instruments occupied locations in Southern India in two deployments from Jan 2000 to June 2002. They then were moved to far Northern India in the Himalya experiment from Sept 2002 to Sept 2003, and then to Central India from Oct 2004 to Oct 2005. Additionally, there are a set of broad-band instruments that occupied sites in the Andaman Islands first from Nov 2003 - Feb 2004 and later, after the great Sumatran - Andaman Islands Earthquake, from Jan 2005 - May 2005. A letter from Dr. Rai accompanying this proposal pledges the delivery of continuous records from all of these installations by the end of CY 2007.

To date, we have received several months of data from NGRI from the year 2000 and have performed quality assurance studies. Cross-correlation results are consistent with carefully installed temporary stations. Figure 14 shows an example of inter-station cross-correlations between stations from the first Southern India installation using data only from Jan 2000. These data, which are the first proof-of-concept data acquired by CU from NGRI, were band-passed between 10 sec and 25 sec for display. Clear arrivals can be seen at both positive and negative correlation lags. The signal-to-noise ratio (SNR) for these estimated Green functions will improve significantly using longer time series. One of the admirable features of each of the five NGRI deployments is that data sets for each station are at least a year in duration. Previous research has shown that a 12-month time series is desired to improve the SNR and also to allow uncertainties in the measurements to be determined from their seasonal variability.

Using an installation of 10 NGRI stations alone, dispersion measurements would be obtained only for 45 inter-station paths. The NGRI deployments are most valuable, therefore, in the context of other stations throughout Central Asia. Stations from the NGRI and PASSCAL experiments are shown in Figure 1 to change and grow substantially in number from 2002 through 2005. FDSN and PASSCAL data are available from the IRIS DMC. The PASSCAL installations are particularly noteworthy. Data from all of the PASSCAL stations

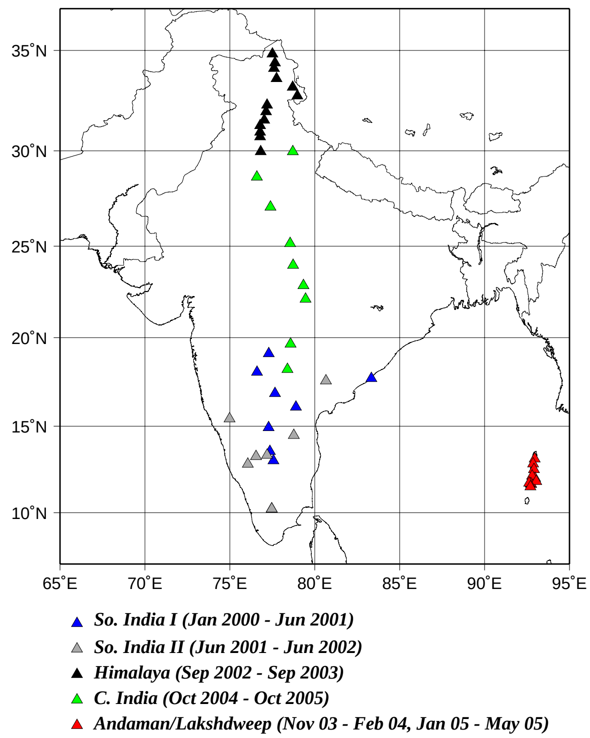

Figure 13: **Blow-up of stations in the five NGRI experiments.**

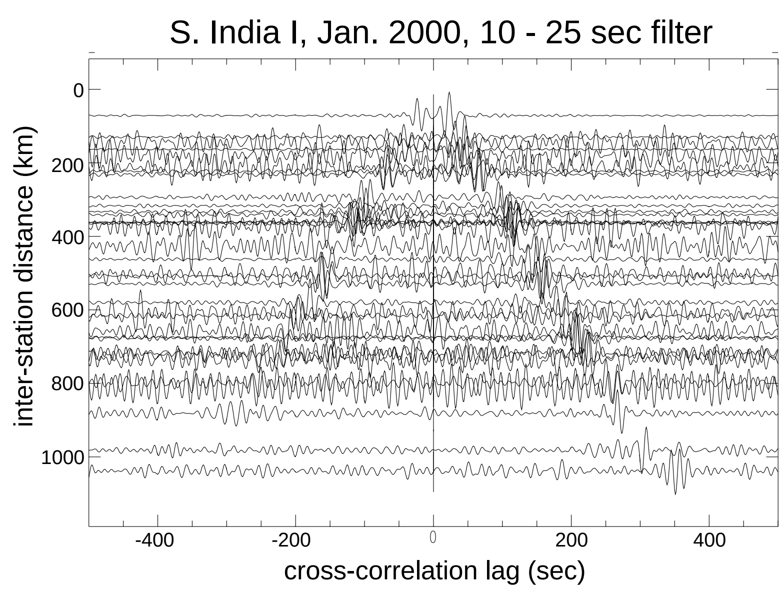

Figure 14: **Preliminary cross-correlations of NGRI data showing the emerging Rayleigh wave Green functions.** Data are a 1-month time series from the S. India Experiment, Phase I in January, 2000, band-passed filtered between 10 and 25 sec period.

shown in Figure 1 should be available for unrestricted access during the contract period (2007-2009).

Therefore, we propose to obtain dispersion measurements from 6 sec to 30 sec period using data from the following networks:

1. Five NGRI experiments (S. India I and II, Himalaya, C. India, Andaman Experiments),
2. PASSCAL experiments within the region of study, and
3. FDSN stations (e.g., GSN, GEOSCOPE, GEOFON) within and around the region of study.

Cross-correlations will be run in each of the six years for which we will have NGRI data (2000 - 2005). Stations will include those from the NGRI experiments, PASSCAL experiments, and permanent FDSN stations within and surrounding the region of study. Both the NGRI and PASSCAL station coverage change appreciably during this period, as Figure 1 shows. The cross-correlations will include those between stations within individual experiments and those across experiments and permanent installations. Letting $\leftrightarrow$ represent cross-correlation, we can depict the data processing symbolically that will be done as follows: NGRI $\leftrightarrow$ NGRI, NGRI $\leftrightarrow$ PASSCAL, NGRI $\leftrightarrow$ FDSN, PASSCAL $\leftrightarrow$ FDSN, $\text{PASSCAL}_i \leftrightarrow \text{PASSCAL}_j$. The notation $\text{PASSCAL}_i \leftrightarrow \text{PASSCAL}_j$ represents cross-correlations performed between stations in different PASSCAL experiments.

2.3.2 Ambient Noise Tomography in India, W. China, and Pakistan

The data processing effort will result in a lattice-work of interweaving paths that is different from that produced by analyzing earthquake data and vastly improved in some regions. Figure 15 depicts the path density that is expected during each of the deployments of the five NGRI experiments compared with path density from the CU-Boulder data set at 12 sec period. The final path density that will emerge will be some overlap of these maps. There are, however, duplications on the maps; e.g., it will not be necessary to compute cross-correlations between FDSN stations every year. In addition, not all stations will report useful data, expected data recovery for PASSCAL experiments is below 90%, and some stations are far enough apart that only low SNR cross-correlations will be returned. We believe, however, that these maps will scale with those that emerge from processing real data and approximately depict the final data coverage. Figure 15 also shows the path density in our current earthquake tomography data set at 12 sec period. Comparison with the expected path density for ambient noise tomography highlights the improvement in both number of data expected from the proposed research as well as the complementation in data distribution.

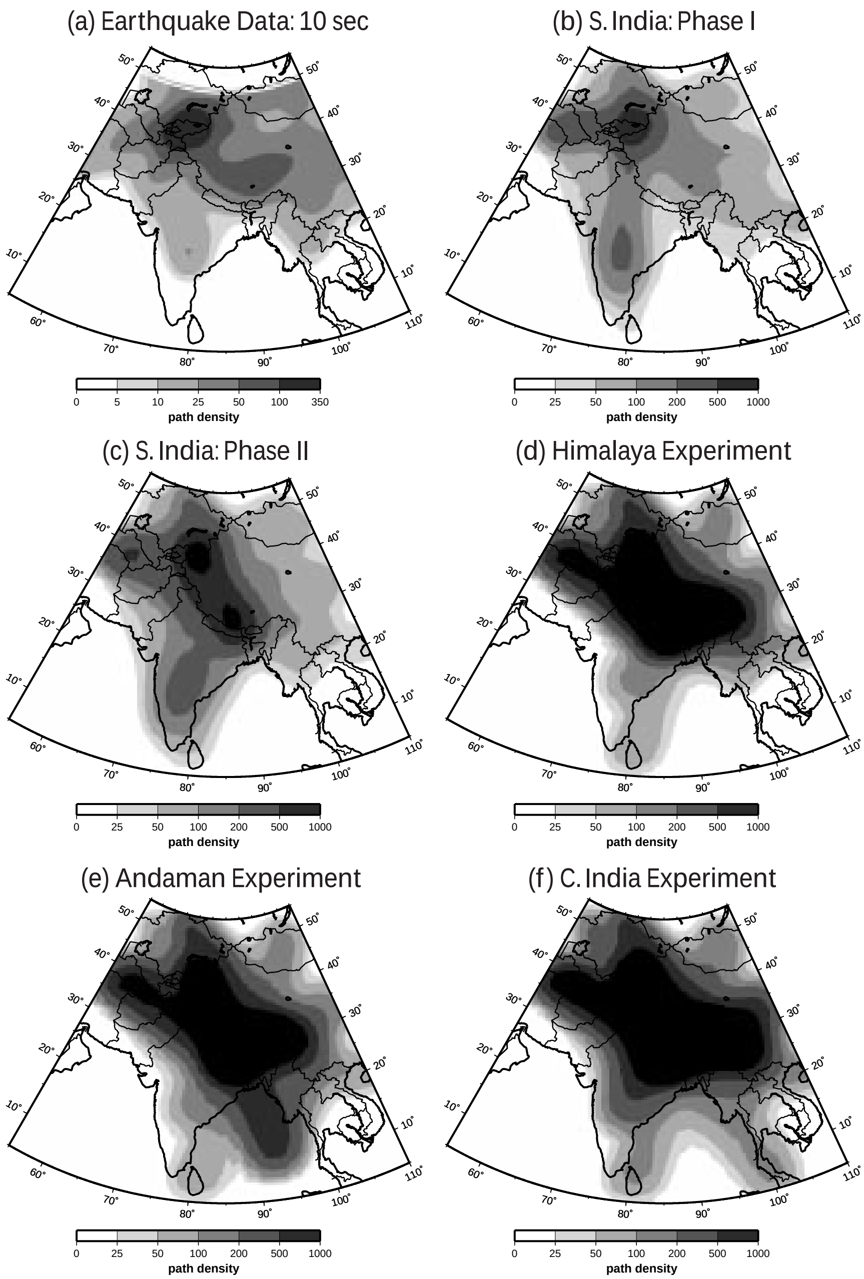

Figure 15: **Path density for earthquake data set compared with that expected from ambient seismic noise.** (a) Path density for the CU-Boulder earthquake data at 10 sec period across C. Asia. The map truncates at 50°N. (b) - (f) The expected path density from inter-station cross-correlations are segregated by time to correspond to the operation of the five NGRI experiments. Path density is defined as the number of paths intersecting each $2^\circ \times 2^\circ$ cell.

The resulting data coverage will vastly improve coverage in India and W. China and also improve coverage in N. Pakistan. Results at short periods (<15 sec) from Europe and North America lead us to expect particular improvements in short period group speed maps relative to the results from earthquake tomography. In addition, resolution is improved further due to the fact that in some areas inter-station paths are shorter than epicentral distances to earthquakes.

Group velocity maps are not only useful for path calibration, they are also valuable information to be included in inversions for 3-D V_s models of the crust and uppermost mantle (e.g., Shapiro and Ritzwoller, 2002; Shapiro et al., 2004). These models, in turn, help to improve regional location capabilities (e.g., Ritzwoller et al., 2003; Yang et al., 2004).

2.3.3 Data Products and Deliverables

There are three data products that will be produced from the proposed research for integration into the DoE Knowledge Base.

Data Product 1. Estimated Green functions. Twelve-month cross-correlations between station-pairs that meet quality control (QC) specifications will be delivered. QC specifications include high signal-to-noise (SNR) ratio and low seasonal repeatability, as discussed in section 2.2.1b above. The resulting set of cross-correlations are considered to be estimated Green functions between the station-pairs.

Data Procuct 2. Measured Dispersion Curves. Group speed curves that are measured on the estimated Green functions between all station-pairs will be delivered. The curves will be accompanied by uncertainty estimates obtained from the seasonal variability of the cross-correlations.

Data Product 3. Group Speed Maps from 6 sec to 30 sec Period. The estimated Green functions and uncertainties provide the basis for group speed tomography across the study region. Group speed maps will be produced on a fine grid of periods from about 6 sec to 30 sec on a $1^\circ \times 1^\circ$ grid across the study region.

The observations (estimated Green functions, dispersion measurements, and uncertainties) made on all of the data used in this study are open for distribution, although waveform data from NGRI are not open-source. No raw waveform data, therefore, will accompany the deliverables. Ambient noise tomography is so new that the utility of the Green functions beyond obtaining dispersion measurements remains poorly understood. We imagine that future studies of attenuation and scattering would find them useful as would using them as Ground Truth for numerical simulations. We believe that it is best, therefore, to save them for delivery to the Knowledge Base rather than discarding them, as the work done here may never be repeated, particulary using the NGRI data in India.

The fourth deliverable will include documentation, reports, and journal publications.

2.4 Benefits of the Teaming Effort: Collaboration with NGRI-Hyderabad, India

The collaboration with Dr. Shyam Rai at the National Geophysical Research Institute in Hyderabad, India is a crucial element of the proposed research. Dr. Rai has already made several months of the S. India deployment (see Fig. 13) available to the PI and associates at CU-Boulder. See Figure 14 for an example cross-correlation record section. He pledges (see accompanying letter) to provide within the year 2006 all broad-band data from the five experiments shown in Figure 13 from early 2000 to late 2005.

The management plan includes yearly face-to-face meetings either in Hyderabad or Boulder. The first meeting will occur in Boulder to ensure complete data delivery and quality control and to train Dr. Rai in ambient noise tomography. The second meeting will occur in Hyderabad in order to install finalized CU-Boulder ambient noise data processing and tomography software at NGRI. The third meeting will be in Boulder to deal with issues related to finalizing the data products, documentation, report writing, and journal publication.

2.5 Complementation with a Companion Proposal from UofI

A companion to this proposal has been submitted by the University of Illinois (UofI) under the direction of Prof. Xiaodong Song in collaboration with the Chinese Earthquake Administration (CEA). The companion proposal is entitled "Surface Wave Dispersion Measurements and Tomography from Ambient Seismic Noise in China". Like the present proposal, the companion is built around the use of a proprietary data set, but the focus is on the Chinese Backbone Network. As Figure 15 demonstrates, the current proposal will deliver much improved data coverage in W. China and India. The companion proposal from UofI/CEA will provide much better coverage in central and eastern China. In addition, there are Chinese backbone stations in W. China that will be brought to bear by the UofI and CEA team that will also improve resolution in W. China.

The current proposal and its companion will, therefore, provide complementary proprietary data products. The application of these data to ambient noise tomography will generate novel results unlike any previous surface wave research performed in Central Asia.

2.6 Facilities

The resources needed to complete the proposed research are largely computational. The proposed work will be carried out using the computing center at the Center for Imaging the Earth's Interior (CIEI). This is an up-to-date facility that includes two multiprocessor file servers from Sun Microsystems, numerous Sun and Linux workstations, several PC clusters, and an assortment of stand-alone PCs and Apple Macintoshes. The center maintains raids and disk storage proportionate to its needs totaling at least 5 Tb. Other peripherals for tape back-up, plotting, scanning, etc. are also in place. The facility is upgraded on a regular basis to meet the growing needs of its users.

2.7 References

Barmin, M.P., M.H. Ritzwoller, and A.L. Levshin, A fast and reliable method for surface wave tomography, Pure Appl. Geophys., 158(8), 1351 - 1375, 2001.

Barmin, M.P., A.L. Levshin, and M. H. Ritzwoller, Finite frequency group velocity sensitivity kernels for surface wave tomography, AGU Fall Meeting, San Francisco, CA, 2005.

Bensen, G.D., M.H. Ritzwoller, N.M. Shapiro, A.L. Levshin, and M.P. Barmin, Broad-band ambient noise tomography across North America, manuscript in preparation, 2006.

Campillo M. and A. Paul, Long-range correlations in the diffuse seismic coda, Science, 299, 547-549, 2003.

Dahlen, F.A. and Y. Zhou, Surface-wave group-delay and attenuation kernels, Geophys. J. Int., 2006.

Levshin, A.L. and M.H. Ritzwoller, Automated detection, extraction, and measurement of regional surface waves, Pure Appl. Geophys., 158(8), 1531 - 1545, 2001a.

Levshin, A.L. and M.H. Ritzwoller, Monitoring a Comprehensive Nuclear Test Ban Treaty: Surface Waves, editors, 243 pps., Birkhauser, Basel, Switzerland, 2001b.

Pasyanos, M.E., W.R. Walter, and S.E. Hazler, A surface wave dispersion study of the Middle East and North Africa for monitoring the Comprehensive Nuclear-Test-Ban Treaty, Pure Appl. Geophys., 158(8), 1445 - 1474, 2001.

Patton, H.J. and L.E. Jones, Surface-wave calibration studies for improved monitoring of a CTBT, 20th Annual Seismic Research Symposium on Monitoring a CTBT, Proceedings, September 21-23, 471-478, 1998.

Rhie, J., and B. Romanowicz, Excitation of earth's incessant free oscillations by Atmosphere-Ocean-Seafloor coupling, *Nature, 431*, 552-554, 2004.

Ritzwoller, M.H. and A.L. Levshin, Eurasian surface wave tomography: Group velocities, J. Geophys. Res., 103, 4839-4878, 1998.

Ritzwoller, M.H., A.L. Levshin, L.I. Ratnikova, Intermediate period group velocity maps across Central Asia, Western China, and parts of the Middle East, Geophys. J. Int., 134, 315-328, 1998.

Ritzwoller, M.H., N.M. Shapiro, M.P. Barmin, and A.L. Levshin, Global surface wave diffraction tomography, J. Geophys. Res., 107(B12), 2335, 2002.

Ritzwoller, M.H., N.M. Shapiro, A.L. Levshin, E.A. Bergman, and E.R. Engdahl, The ability of a global 3-D model to locate regional events, J. Geophys. Res. 108(B7), 2353, ESE 9-1 - ESE 9-24, 2003.

Roux, P., K.G. Sabra, P. Gerstoft, W.A. Kuperman, and M.C. Fehler, P-waves from cross correlation of seismic noise, Geophys. Res. Lett., 2005.

Sabra, K.G., P. Gerstoft, P. Roux, W.A. Kuperman, and M.C. Fehler, Extracting time-domain Green's function estimates from ambient seismic noise, Geophys. Res. Lett. 32, doi:10.1029/2004GL021862, 2005a.

Sabra, K.G., P. Gerstoft, P. Roux, W.A. Kuperman, and M.C. Fehler, Surface wave tomography from microseisms in Southern California, Geophys. Res. Lett., 2005b.

Shapiro, N.M. and M.H. Ritzwoller, Monte-Carlo inversion for a global shear velocity model of the crust and upper mantle, Geophys. J. Int., 151, 88-105, 2002.

Shapiro, N.M. and M. Campillo, Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise, Geophys. Res. Lett., 31, L07614, doi:10.1029/2004GL019491, 2004.

Shapiro, N.M., M.H. Ritzwoller, P. Molnar, and V. Levin, Thinning and flow of Tibetan crust constrained by seismic anisotropy, Science, 305, 233-236, 2004.

Shapiro, N.M. M. Campillo, L. Stehly, and M.H. Ritzwoller, High resolution surface wave tomography from ambient seismic noise, Science, 307(5715), 1615-1618, 11 March 2005.

Snieder, R., Extracting the Green's function from the correlation of coda waves: A derivation based on stationary phase, Phys. rev. E, 69, 046610, 2004.

Stevens, J.L. and S.M. Day, The physical basis of $m_b : M_s$ and variable frequency magnitude methods for earthquake/explosion discrimination, J. Geophys. Res., 90, 3009-3020, 1985.

Tanimoto, T., Excitation of normal modes by atmospheric turbulence: source of long-period seismic noise, Geophys. J. Int., 136, 395-402, 1999.

Villaseñor, A., M.H. Ritzwoller, A.L. Levshin, M.P. Barmin, E.R. Engdahl, W. Spakman, and J. Trampert, Shear velocity structure of Central Eurasia from inversion of surface wave velocities, Phys. Earth Planet. Int., 123(2-4), 169 - 184, 2001.

Weaver, R.L. and O.I. Lobkis, On the emergence of the Green's function in the correlations of a diffuse filed, J. Acoust. Soc. Am., 110, 3011-3017 2001.

Webb, S.C., Broadband seismology and noise under the ocean, Revs. Geophys., 36(1), 105-141, 1998.

Yang, X., et al., Validation of regional and teleseismic travel-time models by relocation of GT events, Bull. Seis. Soc. Am. 94(3), 897-919, 2004.

Yang, Y., M.H. Ritzwoller, N.M. Shapiro, and A.L. Levshin, Broad-band ambient noise surface wave tomography across Europe, manuscript in preparation, 2006.

3. Technical Approach (Statement of Work)

3.1 Objective

The objective is to apply ambient noise tomography to the problem of short period surface wave path calibration in India, W. China, and N. Pakistan. The purpose is to improve the calibration of the surface wave propagation in aseismic areas and at short periods with particular emphasis on monitoring and discrimination of small events using the $M_s : m_b$ discriminant.

3.2 Background

Detection, location, and identification of nuclear explosions by the Air Force Technical Application Center (AFTAC) depend upon calibration of source and path effects to ensure maximum efficiency to monitor at small magnitudes. We propose to apply a new method of surface-wave path effect calibration based on records of ambient seismic noise to advance the calibration capabilities in India, W. China, and N. Pakistan. The method is based on the ability to extract deterministic surface-wave Green functions by cross-correlating long sequences of the ambient seismic (e.g, Shapiro et al., 2005) and will be particularly useful to calibrate surface-wave path effects in aseismic regions and at the short periods needed in nuclear monitoring.

3.3 Approach

The research will be performed by the University of Colorado at Boulder (CU-Boulder) and mission-critical data will be supplied by the National Geophysical Research Institute (NGRI) in Hyderabad, India. The CU-Boulder group will apply a recently developed method of the surface wave dispersion measurement based on long time sequences of ambient seismic noise. They will produce a new dataset of inter-station estimated Green functions, group velocities, and associated uncertainties. These new data will be added to the existing dataset of traditional measurements made from earthquake waves to produce improved group velocity tomographic maps from 6 - 30 sec period across the region of study, which includes most of India, W. and Central China, and N. Pakistan.

The work will progress in four phases:

- **Phase 1.** Obtain broad-band waveform data from the IRIS/DMC and NGRI (India).
- **Phase 2.** Perform data processing to create the data set of inter-station Green functions

- **Phase 3.** Obtain group speed dispersion measurements from 6 sec to 30 sec period with associated uncertainties determined from seasonal variability.
- **Phase 4.** Perform surface wave tomography to create new group speed maps from 6 sec to 30 sec period on a $1^\circ \times 1^\circ$ grid across the region of study.

3.4 Key Deliverables

There are four main deliverables: (1) the new dataset of noise based inter-station estimated Green functions, (2) the group velocity measurements and associated uncertainties, (3) new group velocity tomographic maps, and (4) the reports and publications documenting the application of ambient noise tomography to the study region.

3.5 Tasks

Task 1. Obtain waveform data from the IRIS/DMC and NGRI (India).
Task 2. Apply the ambient noise measurement method to the waveform data to obtain the estimated Green functions.
Task 3. Perform automated dispersion analysis and quality control (QC) measures to obtain group velocity curves and associated uncertainties for all inter-station paths that pass QC.
Task 4. Perform the surface-wave tomography with the combined dataset to create new group velocity maps for the region of study.
Task 5. Documentation and delivery of information to customers at DoE for integration into the DoE Knowledge Base.

3.6 Technical Role and Contributions of Team Members

The CU-Boulder group will lead the collaboration and be responsible for research performance, integration, management and reporting for the team effort and, hence, will be responsible for all Work Items, Tasks, and Deliverables. The NGRI group will deliver data to CU-B for each of the five experiments. See accompanying letter from Dr. Shyam Rai. The NGRI will work with CU-Boulder on data quality control and aspects of the resulting documentation that emerges from the effort.

4. Proposed Schedule

Table 1 presents the time table for the performance of the tasks that constitute the proposed work. Because data from some PASSCAL experiments in China will not become available until 2008, data acquistion from the IRIS/DMC and perhaps from NGRI in India will occur in both Years 1 and 2 of the proposed effort. Each phase of data acquisition will be followed by cross-correlation to obtain the estimated Green functions, group speed measurements and uncertainty information, and surface wave tomography. Documentation and delivery item A refers to the description of results from Year 1, item B refers to description of the finalized results from Years 1 and 2, and item C refers to final delivery of the data products for integration into the DoE Knowledge Base. Working meetings will take place near the middle of each contract year between researchers at CU-Boulder and NGRI, India.

Table 1. Schedule of Performance of the Tasks