ASSESSING ABILITIES TO ESTIMATE SHORT PERIOD GROUP VELOCITIES IN CENTRAL ASIA

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ABSTRACT

Our objective is to develop surface wave group velocity maps to periods as low as 8 s across much of Central Asia. Maps previously estimated at CU-B and Maxwell Technologies were confined to periods above about 15 s. Accurate maps at shorter periods would improve signal detection capabilities by advancing signal-to-noise enhancement produced by phase-matched filters. This may permit the extension of surface wave magnitude (M_s) estimates and the $M_s : m_b$ discriminant to periods shorter than 15 s and, hence, to smaller events than current capabilities allow. Significant advances over existing capabilities are possible because data resources in the region of study have improved dramatically in recent years. Our experience shows that shorter period estimates are possible if sufficient care is taken during the measurement procedure. We have begun data acquisition and processing for this purpose, and present preliminary group velocity maps for short periods across Central Asia, together with estimates of spatially variable resolution and amplitude bias. We also project path coverage and resolution estimates for the anticipated data set.

Key words: **Central Asia, surface waves, group velocities, $M_s : m_b$ discriminant**

OBJECTIVE

The goal of this research is to improve the ability to detect and discriminate small events over wide areas of Central Asia using regional seismic data. We attempt to extend the existing set of Rayleigh and Love wave tomographic group velocity maps to periods shorter than 15 s. Accurate maps at shorter periods would improve signal detection capabilities by advancing signal-to-noise enhancement produced by phase-matched filters. This may permit the extension of surface wave magnitude (M_s) estimates to periods shorter than 15 s and smaller events than current capabilities allow, which is the basis for future tests of $M_s : m_b$ discriminant for these events.

RESEARCH ACCOMPLISHED

Introduction

Seismic calibration of the International Monitoring System (IMS) and other key monitoring stations is critical for effective verification of a Comprehensive Nuclear-Test-Ban Treaty (CTBT). Detection, location, and identification all depend on calibration of source and path effects to ensure maximum efficiency of the IMS to monitor at small magnitudes. The described research that has just started is dedicated to advancing discrimination capabilities for small magnitude events by improving calibration information for surface waves in W. China, Pakistan, N. India, and surrounding areas. The calibration information will be in the form of short period (7 s - 15 s) Rayleigh and Love wave tomographic group velocity maps and station-specific correction surfaces constructed from these maps. Although we have previously provided similar information in the region of study at intermediate periods (15 s - 50 s; e.g., Stevens and McLaughlin, 1997; Ritzwoller et al., 1998; Levshin et al., 1998), the group velocity maps and correction surfaces at short periods will be entirely new. In addition, this new information will be rigorously tested at the CMR Testbed to quantify

the improvement in the ability to estimate surface wave amplitudes and, hence, M_s for smaller events than are currently possible.

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, Stevens and McLaughlin, 2000). To measure surface wave amplitudes accurately in order to estimate M_s is 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 s period (where M_s is usually measured) the regional application of the $M_s : m_b$ discriminant may be improved if M_s were measured at significantly shorter periods; i.e., 8 - 12 s period. To provide these amplitude measurements, it is crucial to be able to reliably detect small amplitude surface waves and accurately measure the corresponding spectral amplitudes. To succeed in both of these efforts requires the ability to predict the group dispersion curves for all source:station paths of interest. It is useful to compress this information into surface wave group travel times or group velocity correction surfaces (e.g., Levshin *et al.*, 1998) from which path corrections can be computed efficiently.

The construction of reliable and robust group velocity maps and correction surfaces at short periods is considerably more challenging than above 15 s period. Because attenuation due to scattering increases at short periods, it is difficult to measure group velocity below 15 s period for paths longer than about 2,500 km. This limits the power of utilizing long paths through the region of study to help homogenize path coverage which has proven so effective in our studies at longer periods. To improve ray coverage using measurements restricted to epicentral distances less than 2,000 - 3,000 km in length implies that it is necessary to process many events smaller in magnitude than those we used previously. Thus, much of the data that we will process will have relatively low signal-to-noise characteristics and great care must be taken in the measurement process. Even with our best efforts, however, short period group velocity maps will not be as reliable or robust as at longer periods, particularly in regions of low station and event coverage such as India. For this reason, we will provide salient information about the quality and reliability of the maps and the group velocity corrections predicted by them.

Maxwell Technologies and the University of Colorado at Boulder are working collaboratively to:

- obtain a new and vastly expanded set of group velocity measurements in the region of study emphasizing measurements between 7 s and 15 s period;
- convert these measurements into group velocity maps and station-specific correction surfaces using both tomographic and model-based methods;
- cross-validate the tomographic and model-based methods to obtain a set of maps and surfaces that are judged most reliable for the area of study;
- embed these maps and surfaces into global maps and surfaces constructed by Maxwell Technologies;
- test and validate the new maps and corrections surfaces with a rigorous set of tests performed on regional data at the CMR Testbed; and
- deliver documentation and reports of all results with the completed maps and surfaces to customers at DoE, CMR, the U.S. NDC, and the IDC.

The final results will be provided in a form that can be easily used within the operational monitoring systems for surface wave identification and phase-matched filtering.

Previous results

The research that we have performed previously in the region of study was primarily dedicated to intermediate periods (15 s - 40 s). It is summarized by Ritzwoller *et al.* (1998) and has been presented at a number of CTBT seismic research symposia (e.g., Levshin and Ritzwoller, 1995a; Levshin *et al.*, 1996, 1997a, 1998; Ritzwoller *et al.*, 1995, 1996) as well as elsewhere (Levshin *et al.*, 1992, 1994, 1997b, 2000a). In our present data set (developed under previous AFTAC, AFOSR, and DSWA funding) we have 850 measurements in the region of study at 10 s period and 3,200 at 15 s period. Figure 1 contrasts path density at periods of 10 s and 15 s for our existing data set. Path density at 15 s is much better than at 10 s partially
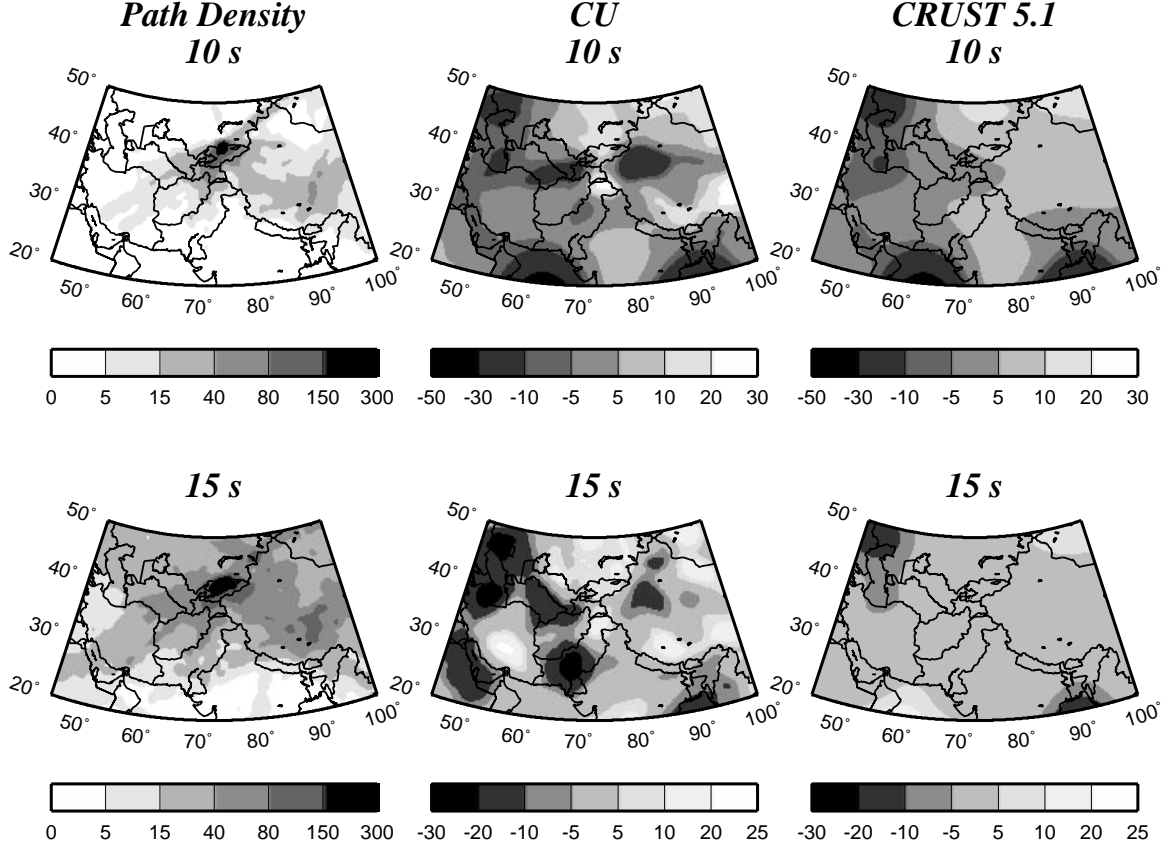
Figure 1: Left Column: Path density for the current data set developed under previous AFOSR, AFTAC, and DSWA funding at 10 s and 15 s periods. Units are number of paths intersecting each $2° \times 2°$ cell ($\sim$50,000 km^2). Middle Column: Our recent Rayleigh wave group velocity maps at 10 s and 15 s periods are presented as perturbation in percent relative to the average across each map. Low velocities are typically sedimentary basins. Right Column: Group velocity maps predicted by a smoothed version of CRUST5.1 (Mooney *et al.*, 1998).

because, at and above 15 s period, measurements can be obtained for paths significantly longer than $\sim$2,000 km, but also because we have not exerted systematic efforts to extract measurements below 15 s period. Clearly, to produce high quality tomographic maps in the region of study at and near 10 s period will require adding more data.

Our tomographic method is discussed by Barmin *et al.* (2000). At each period, we estimate a group velocity perturbation, $\delta U(\theta, \phi)$, relative to an input map, $U_\circ(\theta, \phi)$, which itself may be spatially variable so that group velocity at each spatial point (θ, ϕ) is $U(\theta, \phi) = U_\circ(\theta, \phi) + \delta U(\theta, \phi)$. We typically use a smoothed version of the crustal model CRUST5.1 (Mooney *et al.*, 1998) to compute the input map. We construct $\delta U(\theta, \phi)$ by minimizing the weighted misfit to the data together with both spatial smoothing and model norm regularization constraints. The spatial smoothing constraint determines the wavenumber content of the estimated map. For data that are inhomogeneously distributed, the model norm constraint is very important, and we use path density to determine the strength of this constraint. Where path density is very low (e.g., in the Caspian region at 10 s in Figure 1), $\delta U(\theta, \phi)$ will be strongly damped and constrained to equal the input model.

Figure 1 also presents group velocity tomographic maps at periods of 10 s and 15 s. As discussed above, our tomographic method embeds the tomographic information in an *a priori* model, CRUST5.1, which is also shown in Figure 1 for comparison. The CU and CRUST5.1 maps differ only in those regions where path density is sufficient to allow the CU map to diverge from the *a priori* model. Some means to estimate the quality of group velocity maps are discussed at length by Barmin *et al.* (2000). Two of the most useful
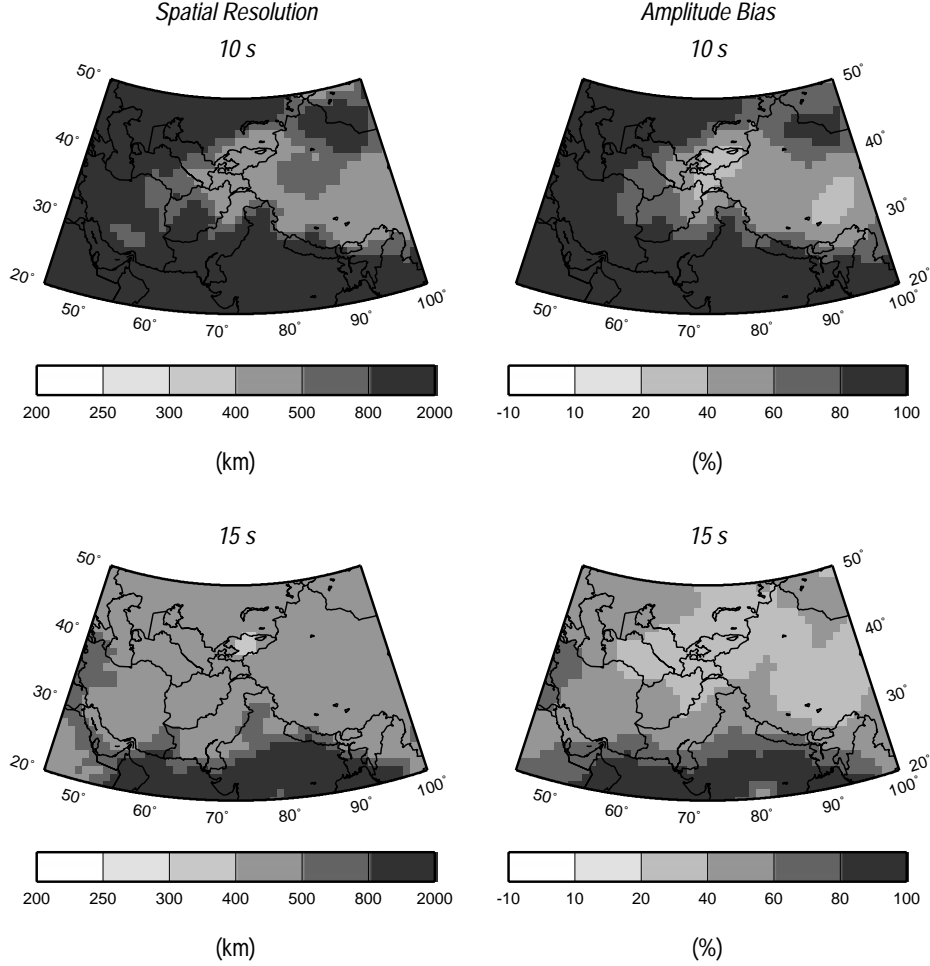
Figure 2: Spatial resolution and amplitude bias estimated for our current data set at periods of 10 s and 15 s. Resolution is in km and amplitude bias is in percent. Note that for amplitude bias, 0% is optimal, and >50% is very big. The salient conclusion is that the current quality of our 15 s maps is much better than the 10 s maps.

qualitative measures are spatially variable resolution and amplitude bias. The estimation of the resolution at a given point on the map is obtained by using the appropriate row of the resolution matrix which characterizes the tomographic image. We define resolution as a radius, σ, of the base of the cone fitted to the resolution function at each point of the grid. To determine the amplitude bias we move a cylindrical perturbation with the 'width', $2\sigma(\theta, \phi)$, around the region of study, perform tomography on the synthetic travel times traced through the test function for the given data set, and investigate the capability to reproduce the test function given the chosen regularization parameters, data characteristics, weighting, etc. Amplitude bias is defined as the relative difference (in percent) of the amplitude of the fit cylinder to the amplitude of the input cylinder at each grid point. Figure 2 presents spatial resolution and amplitude bias of the maps in Figure 1 and contrasts the 10 s and 15 s maps with respect to these measures of map quality.

The quality of the 10 s map is spatially highly variable; west of about the 60°E, north of 45°N, and south of 30° the maps will result almost entirely from the input map, CRUST5.1. The resolution and amplitude bias of the 10 s maps are far worse than at 15 s and major features, such as the Dzungarian Basin in W. China, are entirely missing in Figure 1. Nevertheless, the 10 s map can be considerably improved once systematic efforts are dedicated to adding measurements at and below 10 s period.

Figure 3 presents station specific correction surfaces for the group velocity of the 15 s Rayleigh wave at four stations: AAK, ABKT, WMQ, and WUS (GEOSCOPE station). These surfaces were constructed

by accumulating travel time perturbations through the 15 s map shown in Figure 1 along the great circle linking each point on the group velocity map to the specified station and then assigning that time to the spatial point on the correction surface. Thus, correction surfaces differ strongly for different stations. The group velocity correction for the 15 s Rayleigh wave for the specified station for an event at any location on these maps can simply be read from the map. Because the ray tracing has been done in the construction of the correction surfaces, these maps can be used efficiently, even in real-time, to help identify events (Levshin *et al.*, 2000b). Except for isolated areas that have seen substantial empirical calibration efforts (e.g., much of W. China surrounding Lop Nor), the maps in Figure 3 may be the best correction surfaces currently in existence for the entire region of study. They can be improved considerably, however, at 15 s and below.

Group Velocity Correction Surfaces

15 s Rayleigh Wave

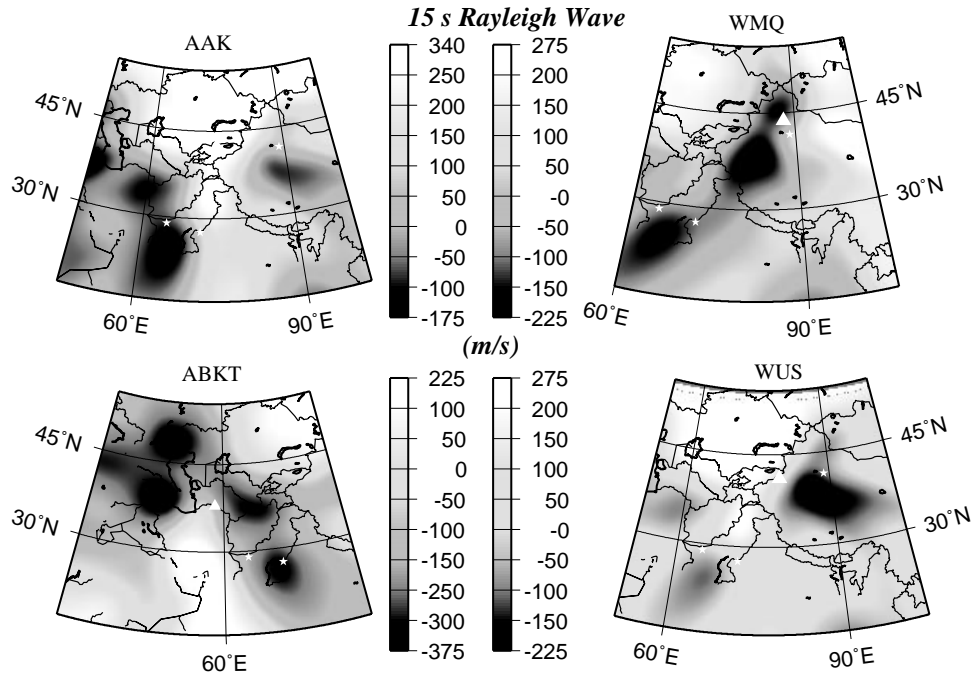Reference value of Group Velocity 2.77 km/s

Figure 3: Group velocity station specific correction surfaces for our 15 s Rayleigh wave map shown in Figure 1. The specified stations are indicated on each figure with a triangle, and the Chinese, Pakistani, and Indian test sites are shown with stars.

Recent work done by Maxwell Technologies has focused on techniques for improving surface wave measurements and reducing the surface wave detection threshold, and on development of MAXSURF, the code used at the IDC and PIDC for automatic identification and measurement of surface waves. MAXSURF is responsible for all surface wave processing at the IDC and the PIDC and runs in the processing stream after events have been identified and located. MAXSURF then examines the arrival window where a surface wave would be expected and applies a dispersion test to see if a surface wave can be identified. If so, then the amplitude is measured and stored in the IDC database. Surface waves are identified in the following way: a set of narrow band filters are applied to the data over a set of 8 periods from 16 s to 50 s. A long-period or broadband beam is formed at arrays with the expected azimuth and slowness. The arrival times at each frequency are then compared with predicted arrival times generated from the regionalized group velocity model. Postprocessing techniques have been developed to remove spurious or misassociated arrivals. This type of automatic processing has proven to work very well, and the detection threshold for the IMS network is nearly an order of magnitude lower than the detection threshold for other networks where surface waves are identified visually. Figure 4 shows a comparison of the cumulative distribution of detected arrival amplitudes for the IMS network as reported in the Reviewed Event Bulletin (REB) and the surface

Cumulative Distribution

0.001
0.01
0.1
1

1 2 3 4 5 6

Log Amplitude (nm)

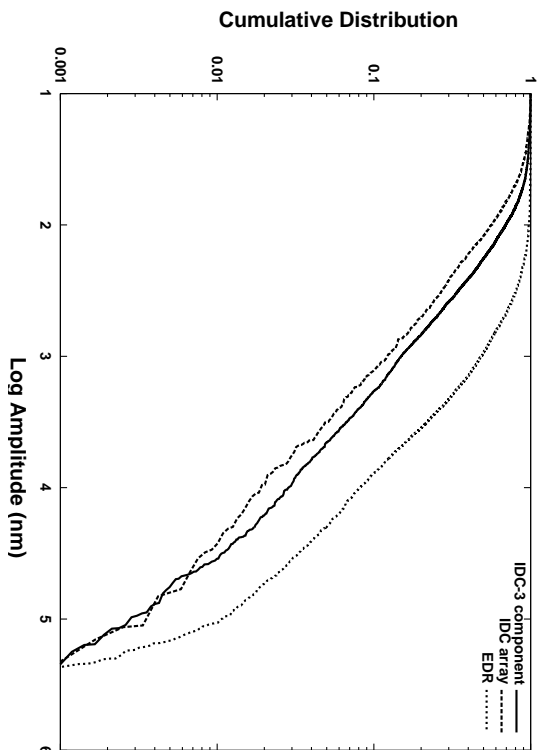IDC-3 component ———
IDC array ·········
EDR ·········

Figure 4: Cumulative distribution of IDC and EDR amplitudes. This figure shows that the IDC detection threshold is approximately one magnitude unit lower than the EDR detection threshold.

waves reported in the Earthquake Data Reports (EDR) produced by the USGS, showing this difference.

This example demonstrates the importance of good group velocity maps. Because surface waves are identified by comparison with predicted arrival times, it is essential that the predicted group velocities are accurate. One way to reduce the threshold further is to increase the frequency band over which surface waves can be measured. The current band of 16 s - 50 s period was found to be a good band for worldwide surface wave data measured at distances of 20-100 degrees, and the global dispersion maps are fairly well defined over this period band. However, at shorter distances, surface waves are dominated by higher frequencies. To improve signal to noise ratio and to measure surface waves at close range, the dispersion test and measurement of surface waves should be performed at higher frequencies. There are currently few measurements available in the 7-15 s period range, and the global group velocity maps are, therefore, not well defined in this band. Good data in this frequency band is required in order to develop the dispersion curves needed for identification of surface waves and phase-matched filtering at regional distances.

Improving Group Velocity Measurements and Maps

The planned work is based on the premise that careful and dedicated efforts devoted to obtaining accurate group velocity measurements at short periods (<15 s) will greatly improve the quality of the 7 s - 15 s group velocity maps, particularly at the short period end. The rationale for this is presented in Figure 5, which shows two frequency-time diagrams for two events of similar magnitude with different path lengths of ~3,000 km and ~1,000 km, respectively. This figure demonstrates the difficulty in obtaining group velocity measurements below periods of about 12 s for paths longer than about 2,000 km. For paths less than about 2,000 km in length, Rayleigh waves can be observed and group velocities estimated regularly to periods of 6 s or 7 s for events with M_s as low as ~4.2 - 4.5 if sufficient care is taken to extract the signal and separate the fundamental mode from Lg, the first overtone, and potential multipaths.

The key to improving tomographic capabilities at short periods is to introduce measurements for paths less than about 2,000 - 2,500 km in length. Fortunately, there are many events in the region of study, although the station distribution is far from optimal. Figure 6 shows the 40 stations (GSN, GEOSCOPE, GEOFON, KNET, KAZNET, CDSN, Saudi Arabian Network) and ~ 1200 earthquakes (PDE; $m_b \geq 4.0$; 1996-1999) from which we will process data in the proposed work. Taking into account that the number of simultaneously operating stations is always substantially less, the number of measurements for this three-year long time interval is expected to be about 15,000. Clustering the group velocity curves will produce 5,000 - 10,000 unique paths. Figure 7 shows the resulting path density if we augment our current data set
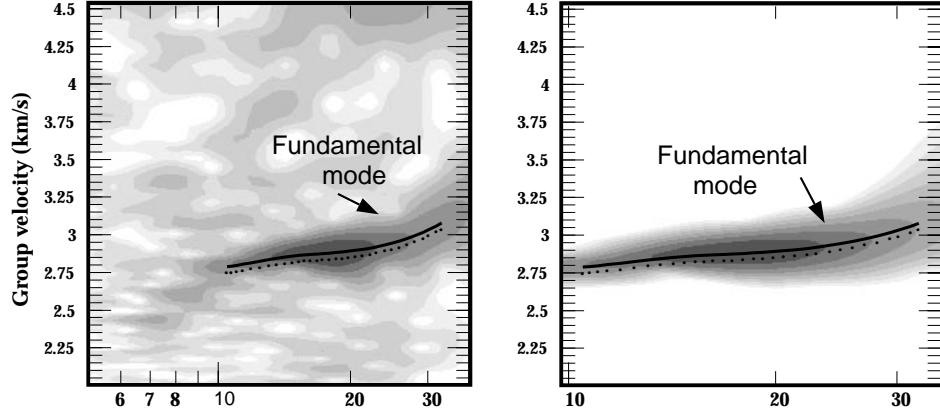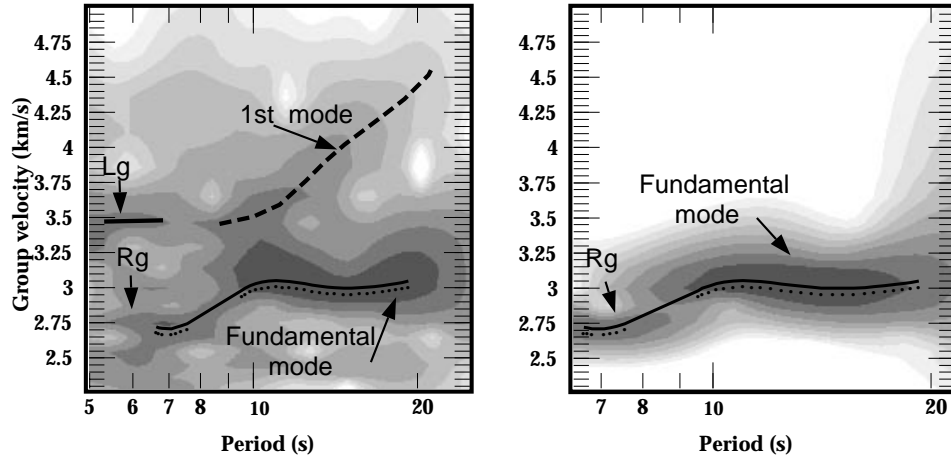
Figure 5: Frequency-time diagrams for two events and paths indicated on the figure. Measurements below about 12 s period are obtained more reliably on shorter paths. (HYB - Hyderabad, India; WUS - Wushi, China).

at the 10 s period (~850 measurements) with ~9,900 additional measurements for the stations and events in Figure 6, in which a path is chosen only if meets the following epicentral distance and magnitude criteria: $\Delta \leq 1,500$ km if $4.0 \leq m_b \leq 4.2$, $\Delta \leq 1,750$ km if $4.2 < m_b \leq 4.4$, and $\Delta \leq 2,000$ km if $m_b > 4.4$. From this analysis we expect significant improvement in path coverage in W. China, Pakistan, Afghanistan, Iran, and the surrounding areas. Because of the shortage of both stations and events in India, however, significant improvement in path density in India will be difficult to attain.

The introduction of measurements for the sources and receivers in Figure 6 would have a profound effect on the quality of the Rayleigh wave group velocity maps at and below 10 s period. Figure 8 shows spatial resolution and amplitude bias for the data set described in Figure 6. Resolution and amplitude bias are tremendously improved relative to the 10 s map of Figure 2, but India remains very challenging.
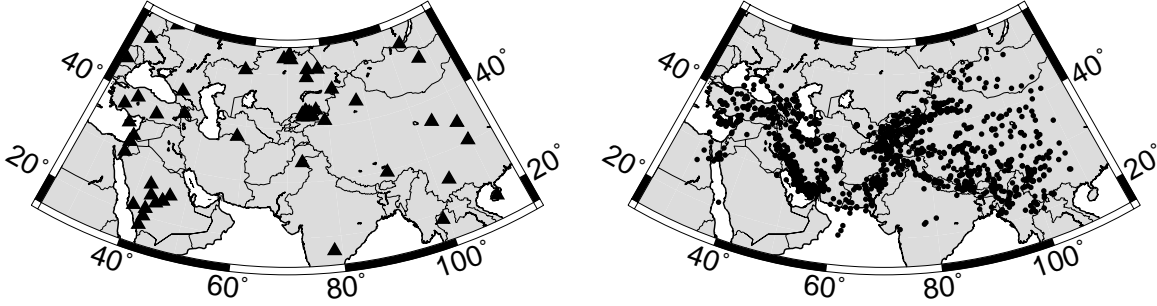
Figure 6: Stations (∼40 from GSN, GEOSCOPE, GEOFON, KNET, KAZNET, CDSN, Saudi Arabia Network) and events (∼1200; PDE m_b ≥4.0; 1996 - 1999) to be used in the proposed research.
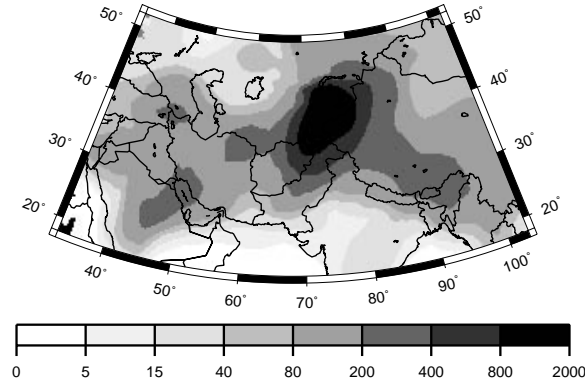

Figure 7: Estimate of the 10 s Rayleigh wave path density (see Figure 1 for definition) that will result from the proposed research; that is, if we augment our current data set at 10 s period (∼850 measurements) with ∼ 15,000 additional measurements for the stations and events in Figure 6 in which a path is chosen only if it meets the following epicentral distance and magnitude criteria: Δ ≤1,500 km if 4.0≤ m_b ≤ 4.2, Δ ≤1,750 km if 4.2< m_b ≤ 4.4, and Δ ≤2,000 km if m_b > 4.4. Contrast with Figure 1, left column.

CONCLUSIONS AND RECOMMENDATIONS

Work on the described project is in its early stage of acquiring and preprocessing waveform data from various networks: GSN, GEOSCOPE, GEOFON, KNET, KAZNET, Saudi Arabian Network, and CDSN stations following the 1200 events that occurred in 1996-1999 (stations and events in Figure 6). The following stages of the work are planned:

- Obtain group velocity measurements at and above ∼7 s period.

- Produce Rayleigh and Love wave group velocity maps in increments of 1 s from 7 s to 15 s periods for the region of study by the tomographic method. Produce resolution and amplitude bias maps at each wave period.

- Convert the group velocity maps to station specific correction surfaces for IMS and other interesting stations in and adjacent to the region of study.

- Incorporate the group velocity measurements into new global group velocity maps by the model-based method.

- Cross-validate group velocity maps obtained by the tomographic and model-based methods.

- Deliver measurements and maps from CU-B to Maxwell Technologies and customers.

- Test and validate the maps and correction surfaces on IMS data at the CMR Testbed.
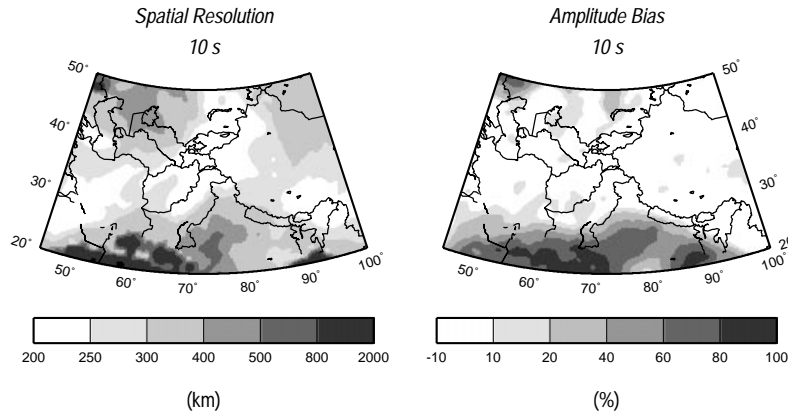
Figure 8: Estimate of the spatial resolution and amplitude bias for the 10 s Rayleigh wave which will arise from the proposed research; i.e., for the paths described in Figure 6. Contrast with the current state in Figure 2. The conclusion from Figures 7 and 8 is that the proposed research is guaranteed to provide substantial improvement in group velocity maps at ∼10 s period across most of the region of study. The principal caveat is that India, except for the far north, presents a very challenging target.

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