SHORT PERIOD SURFACE WAVE DISPERSION MEASUREMENTS FROM AMBIENT SEISMIC NOISE IN NORTH AFRICA, THE MIDDLE EAST, AND CENTRAL ASIA

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ABSTRACT

We have begun to apply ambient noise surface wave tomography to broad-band seismic data obtained in North Africa, the Middle East, and Central Asia. The goal is to improve the calibration of surface wave propagation in aseismic areas.

The basic idea of the method is that ambient seismic noise contains a significant component of Rayleigh wave energy that is excited by oceanic microseisms and atmospheric forcing. Rayleigh wave Green functions can be extracted by computing cross-correlations between records by using observations over several days or months at pairs of seismic stations. Group velocities are then measured by applying frequency-time analysis to the waveforms emerging from the cross-correlations and traditional surface wave tomography is then performed.

The method was first systematically applied in California where cross-correlating one month of ambient seismic noise yielded hundreds of short-period (5 sec - 18 sec) surface-wave group-velocity measurements that have been used to construct tomographic images reflecting the principal geological units within California. More recently, we have applied the method at larger spatial scales and longer periods by computing cross-correlations and making surface-wave group velocity measurements for paths connecting more than one hundred broadband stations in North America. This is now producing thousands of broad-band group velocity measurements (10 sec - 150 sec) for stations separated by several hundred to a few thousands kilometers.

Here we present the results of the first application of the ambient noise measurement method to broadband seismic data located in North Africa, the Middle East, and Central Asia as a step toward calibrating the propagation of surface waves in this region.

OBJECTIVE(S)

The objective of this research is to obtain short and intermediate period (7 - 30 sec) surface wave dispersion measurements from ambient seismic noise and use these measurements to produce dispersion maps for North Africa, the Middle East, and Central Asia. The ultimate purpose is to improve the calibration of surface wave propagation in aseismic areas and at short periods with particular emphasis on the monitoring and discrimination of small events using the Ms:mb discriminant.

RESEARCH ACCOMPLISHED

Background

Ambient seismic noise is excited by randomly distributed natural and artificial sources and, when considered over sufficiently long times, includes surface waves propagating in all directions. Ambient noise, therefore, contains information about surface wave propagation as well as 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, 2001a; Snieder, 2004). The use of ambient noise to extract Green functions has been applied successfully in a number of fields, including helioseismology (e.g., Duvall et al., 1993; Kosovichev et al., 2000; Rickett and Claerbout, 2000), ultrasonics (e.g., Weaver and Lobkis, 2001a, 2001b, 2002, 2003; Derode et al., 2003a, 2003b), exploration seismology (e.g., Schuster et al., 2004; Wapenaar, 2004), and marine acoustics (e.g., Roux et al., 2003).

In seismology, two types of signals have been considered to compose random wavefields and utilized to infer Green functions by cross-correlation. Most of the research using both types of random wavefields has been performed using data from North America. 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 and atmospheric disturbances (e.g., Lognonne et al., 1998; Tanimoto, 1999; Roult and Crawford, 2000; Fukao et al., 2002). By correlating vertical records of ambient noise at stations separated by distances ranging 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 cross-correlations. The method has been used to produce group velocity tomography maps between 7 and 20 sec period for Southern California by Shapiro et al. (2005) (see Fig. 1) and Sabra et al. (2005b).

Cross-correlating long time series to produce surface wave Green functions remains in its formative stages and the applications discussed above have been largely proof-of-concept experiments. It is clear, however, that this method possesses several key advantages over tradition surface wave tomography using teleseismic earthquakes. First, the cross-correlation method can be applied to relatively short paths between stations located in aseismic areas which improves resolution in areas that are well instrumented. Second, the new measurements can be extended to periods considerably shorter than 20 sec, which is important for monitoring small seismic events. Third, the new measurements are relatively unaffected by seismic source location and phase and, therefore, are relatively free of these potential sources of bias that affect traditional surface wave measurements. Fourth, the measurements are naturally repetitive and their uncertainties can be estimated by processing different time windows of the noise records.

Application on a Continental Scale Across North America

To date, the application of surface wave ambient noise tomography has been restricted to relatively small regions (notably Southern California) for periods below 20 sec. No results have been published yet on a continental scale or for periods above 20 sec. Even before USARRAY, broad-band data from 125 stations are available across or near the United States (Fig. 2) from the IRIS DMC. We are using these stations as a test-bed to develop the cross-correlation method on a continental scale. The fact that broad-band Green functions can be recovered from recordings at stations separated by up to several thousand km was first established by Shapiro and Campillo (2004). An example of cross-correlations for several period bands is shown in Figure 3 for a one month time series observed at two GSN stations (CCM - Cathedral Cave, MO; HRV - Harvard, MA).

The cross-correlograms can be used to measure group speeds between station pairs. Although we are compiling results at shorter and longer periods, we show results here only at 16 sec period. At present, our data set for the United States consists of cross-correlograms stacked over a four month period (Nov. 2003 - Feb. 2004). (Cross-correlograms for longer time series are being computed as this paper is being written.) Group speed measurements are obtained for both positive and negative lags on the cross-correlogram, corresponding to waves propagating in opposite directions between the two stations. In principle, the stations shown in Figure 2 could provide 7750 independent group speed measurements. We require, however, a level of consistency between positive and negative lag measurements and accept measurements only if the signal-to-noise is greater than 10. This reduces the number of acceptable measurements appreciably. For example, at 16 sec period the number of measurements reduces to 4508. These paths are shown in Figure 4a.

The 16 sec group speed measurements obtained on the paths shown in Figure 4a can be used as data in standard surface wave tomography (e.g, Barmin et al., 2001; Ritzwoller et al., 2002). Previous work resulted in a large data set of teleseismic group speed measurements (e.g., Ritzwoller and Levshin, 1998; Ritzwoller et al., 1998; Pasyanos et al., 2001) that has been used to produce a global shear velocity model of the crust and upper mantle (e.g., Shapiro and Ritzwoller, 2002). The 16 sec group speed map from this model (shown in Figure 4b) is used as the reference model for tomography based on more than 4500 group speed measurements obtained by the cross-correlation method. The reference map is then used as a background for the high-resolution tomography. The revised 16 sec group speed map obtained on a 1x1 degree grid across the US and adjacent regions is shown in Figure 4c. This map has much higher resolution than the reference map and displays significantly smaller features that in most cases are correlated with known structural features (such as a number of sedimentary basins across the US).

The research on short and intermediate period surface wave tomography from ambient seismic noise is continuing across the US as a guide to the development of the cross-correlation method on a continental scale. A particularly relevant area of further research involves subsetting the input time series to allow error estimates of the measured group speeds.

Preliminary Application Across Eurasia and North Africa

The North American data set is a test-bed for the application of ambient noise tomography to the coarser station coverage that exists on the larger scales of Eurasia. Work has begun to develop a similar data set across much of Eurasia and North Africa. The preliminary station distribution identified for use in this study is shown in Figure 5. The results presented here are for one-month time series acquired in Jan. 2004. At the time of writing, computation of cross-correlations for all stations in the one-month data set have not yet completed so we show only sample results on the completed subset. The near term goal is to acquire data for all of 2004 and apply ambient noise tomography between 7 sec and 30 sec period.

Early results indicate that ambient noise Green functions across Eurasia have similar signal-to-noise properties as those acquired across North America. Cross-correlations in several pass-bands between stations in China for a single month of data are shown in Figure 6. Examples of typical receiver gathers are shown in Figure 7 for the band between 10 and 20 sec period.

Source of the Broad-Band Signal

More work needs to be done to understand the nature and variability of the ambient noise, although this is beyond the scope of the current contract. The source of ambient noise at periods below 20 sec is probably pretty well understood to be primary (12 - 18 sec) and secondary microseisms (6 - 9 sec) occurring in shallow waters in a several hundred km band offshore. The primary microseism results from the direct interaction between the oceanic surface gravity wave and the seafloor through the exponential decay of pressure with depth. The secondary microseism results from the frequency doubling effect of the nonlinear wave-wave interaction between the incoming and reflected primary surface gravity waves. Although this source mechanism is understood generally, the spatial location and temporal (e.g., seasonal) variability of the source as well as how these waves will be observed across the region of study remains only dimly perceived as is the variation of these variables with wave frequency. More dimly perceived still is the source and nature of the ambient noise at periods longer than the primary microseism band. Presumably, at least until very long periods (i.e., above 150 sec), the source regions will be predominantly oceanic. Whether this is true and what the spatial and temporal distribution of sources are remains unclear. A truly informed application of the cross-correlation method will require the resolution of these questions.

CONCLUSION(S) AND RECOMMENDATION(S)

(1) Ambient noise surface wave tomography provides higher resolution tomographic images than traditional teleseismic surface wave tomography in regions where inter-station spacing is on average smaller than epicentral distances.

(2) The cross-correlation method yields broad-band Rayleigh wave Green functions on a continental scale both across North America and Eurasia.

Further work continues in the development of error estimates for the measured group speeds using data subsetting, in the development of a year long data set (2004) for about 120 stations across Eurasia and North Africa, and in the application of ambient noise tomography to data set from periods ranging from about 7 sec to 30 sec.

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REFERENCE(S)

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

Butler, R., T. Lay, K. Creager, P. Earle, K. Fischer, J. Gaherty, G. Laske, B. Leith, J. Park, M. Ritzwoller, J. Tromp, and L. Wen (2004), The global seismic network surpasses its design goal, *Eos.* 85(23).

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

Derode, A., E. Larose, M. Tanter, J. de Rosny, A. Tourin, M. Campillo, and M. Fink (2003a), Recovering the Green's function from field-field correlations in an open scattering medium, *J. Acoust. Soc. Am*. 113, 2973-2976.

Derode, A., E. Larose, M., Campillo, and M. Fink (2003b), How to estimate the Green's function of a heterogeneous medium between two passive sensors? Application to acoustic waves, *Appl. Phys. Lett*. 83, 3054-3056.

Duvall. T.L., S.M. Jefferies, J.W. Harvey, and M.A. Pomerantz (1993), Time distance helioseismology, *Nature* 362, 430-432.

Fukao, Y., K. Nishida, N. Suda, K. Nawa, and N. Kobayashi (2002), A theory of the Earth's background free oscillations, *J. Geophys. Res*. 107, 2206, doi:10.1029/2001JB000153.

Kosovichev, A.G., T.L. Duvall, and P.S. Scherrer (2000), Time-distance inversion methods, *Solar Phys*. 192, 159-176.

Lognonne, P., E. Clevede, and H. Kanamori (1998), Computation of seismograms and atmospheric oscillations by normal-mode summation for a spherical earth model with realistic atmosphere, *Geophys. J. Int*. 135, 388-406.

Pasyanos, M.E., W.R. Walter, and S.E. Hazler (2001), 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.

Rickett, J.E. and J.F. Claerbout (2000), Calculation of the Sun's impulse response by multi-dimensional spectral factorization, *Solar Phys*. 192, 203-210.

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

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

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

Roult, G. and R. Crawford (2000). Analysis of 'background' free oscillations and how to improve resolution by subtracting the atmospheric pressure signal, *Phys. Earth Planet. Int.* 121, 325-338.

Roux, P., H.C., Song, and W.A. Kuperman (2003), Time-reversal using ambient noise as a probe source, *J. Acoust. Soc. Am.* 113, 2218.

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

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

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

Schuster, G.T., J. Yu, J. Sheng, and J. Rickett (2004), Interferometric/daylight seismic imaging, *Geophys. J. Int.* 157, 838-852.

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

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

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

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

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

Wapenaar, K. (2004), Retrieving the elastodynamic Green's function of an arbitrary inhomogeneous medium by cross correlation, *Phys. Rev. Lett.* 93, 254301.

Weaver, R.L. and O.I. Lobkis (2001a), Ultrasonics without a source: thermal fluctuation correlation at MHz frequencies, *Phys. Rev. Lett.* 87, 134301-134304.

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

Weaver, R.L. and O.I. Lobkis (2002), On the emergence of the Green's function in the correlations of a diffuse field: pulse-echo using thermal phonons, *Ultrasonics* 40, 435-439.

Weaver, R.L. and O.I. Lobkis (2003), Elastic wave thermal fluctuations, ultrasonic waveforms by correlation of thermal phonons, *J. Acoust. Soc. Am.* 113, 2611-2621.

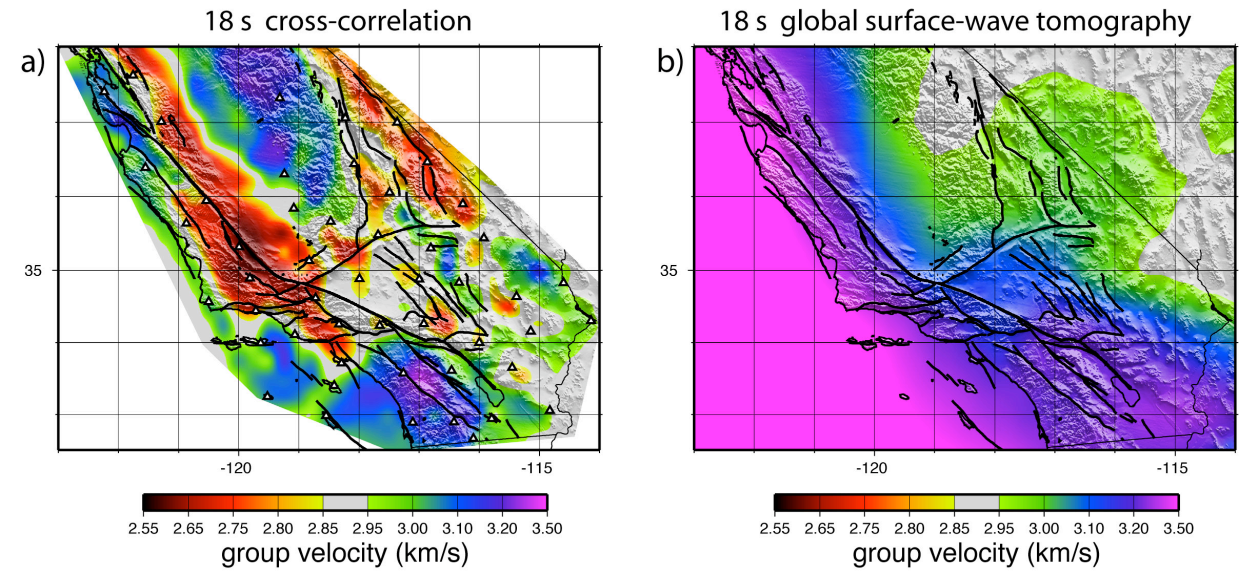

Figure 1. Ambient noise tomography compared with traditional global teleseismic tomography across Southern California. (a) The 18 sec group speed map on a 0.25 degree grid derived from group speeds measured on cross-correlations between 62 USARRAY Transportable Array stations. (b) The 18 sec group speed map derived from global teleseismic tomography, presented for comparison. Ambient noise tomography provides much better lateral resolution than traditional tomography, particularly in the context of a regional array.

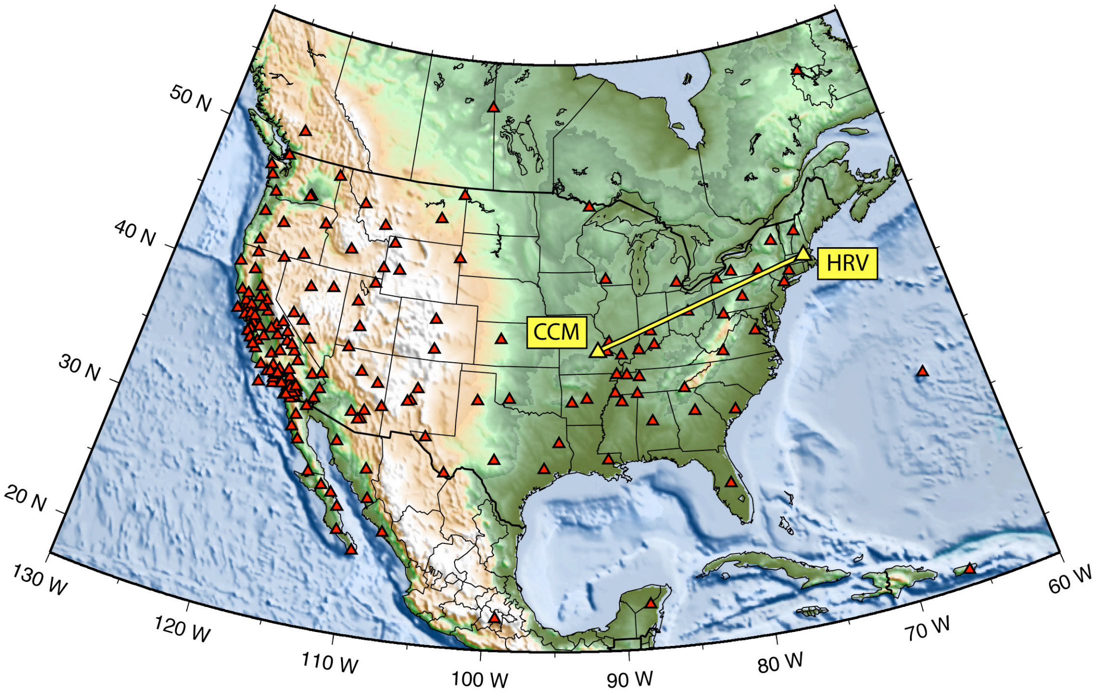

Figure 2. Current backbone network across the US. As a test-bed for continental scale tomography across Eurasia and North Africa, 125 broad-band stations (red triangles) are used within and surrounding the US. The path between GSN stations CCM (Cathedral Cave, MO) and HRV (Harvard, MA) is highlighted, and corresponds to the cross-correlations shown in Figure 3.

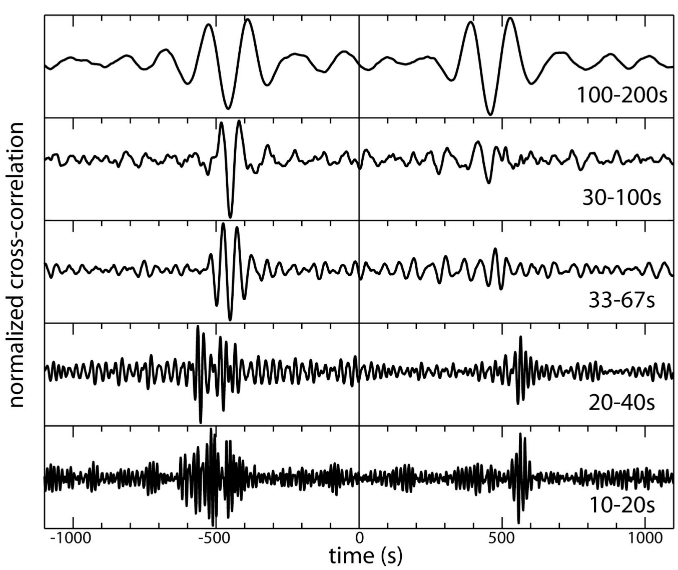

Figure 3. Broad-band cross-correlations between two North American GSN stations: CCM (Cathedral Cave, MO) and HRV (Harvard, MA). The cross-correlations are for 1 month of data from November, 2003. The time axis is the cross-correlation lag (in sec). In this case, positive lag corresponds to waves traveling from CCM to HRV and negative lag to waves from HRV to CCM. The pass band in each case is indicated.

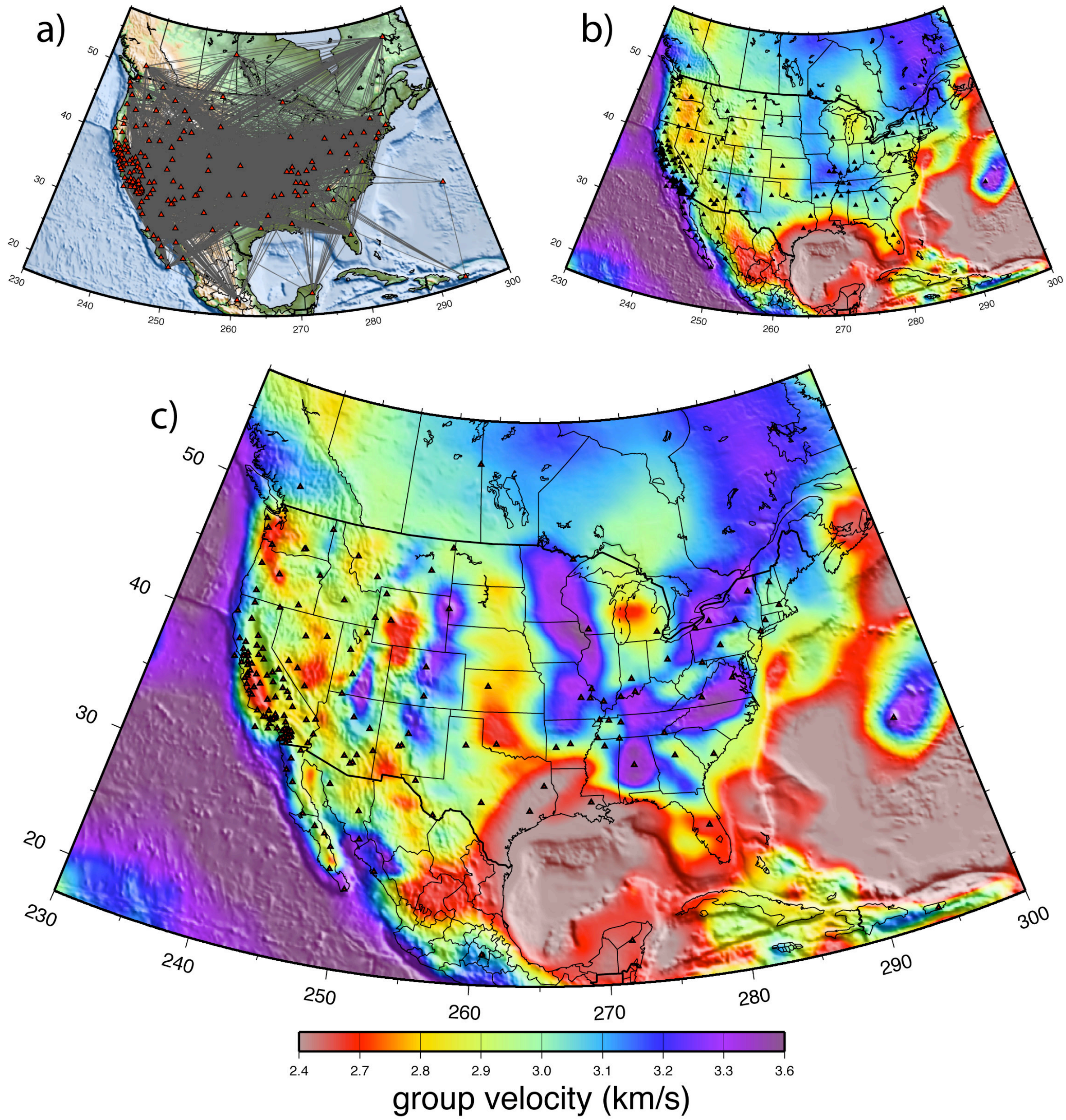

Figure 4. Results of ambient noise group speed tomography across the US at 16 sec period. (a) Coverage of the ~4500 paths composing the data set at 16 sec period. Each group speed measurement is obtained from a four month cross-correlation (Nov. 2003 – Feb. 2004) with a signal-to-noise ratio greater than 10. (b) The 16 sec group speed reference map is computed from the 3D shear velocity model of Shapiro and Ritzwoller (2002). This map is used as both a starting point and background model for the ambient noise tomography. (c) Results of ambient noise tomography using only the group speed measurement obtained from the four-month cross-correlations. The map is produced on a 1 degree grid across the region and provides a 65% variance reduction relative to the reference map in (b).

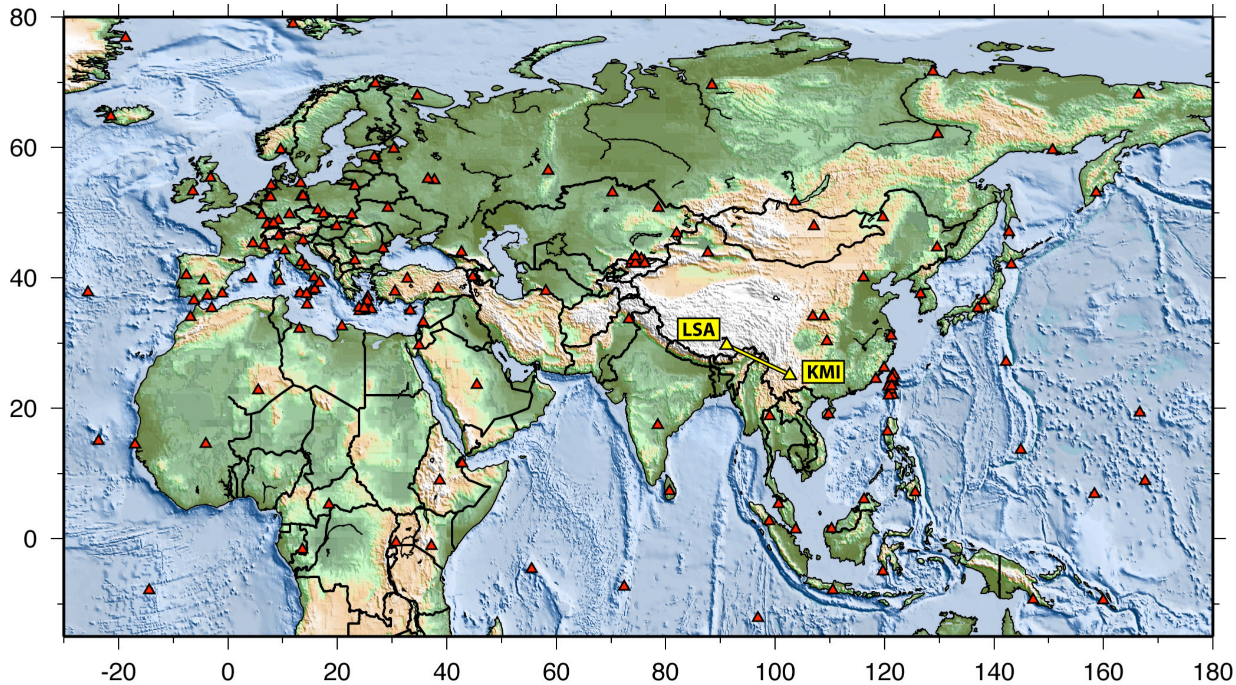

Figure 5. Broad-band stations (red triangles) to be used for tomography across Eurasia and North Africa. The path between GSN stations LSA (Lhasa, Tibet) and KMI (Kunming, China) is highlighted, and corresponds to the cross-correlations shown in Figure 6.

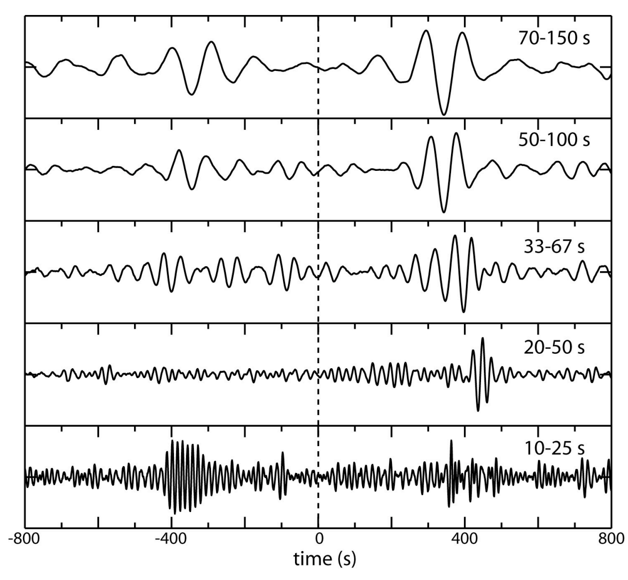

Figure 6. Broad-band cross-correlations between two Asian GSN stations: LSA (Lhasa, Tibet) and KMI (Kunming, China). The cross-correlations are for 1 month of data from January, 2004. The time axis is the cross-correlation lag (in sec). In this case, positive lag corresponds to waves traveling from KMI to LSA and negative lag to waves from LSA to KMI. Each pass-band is indicated.

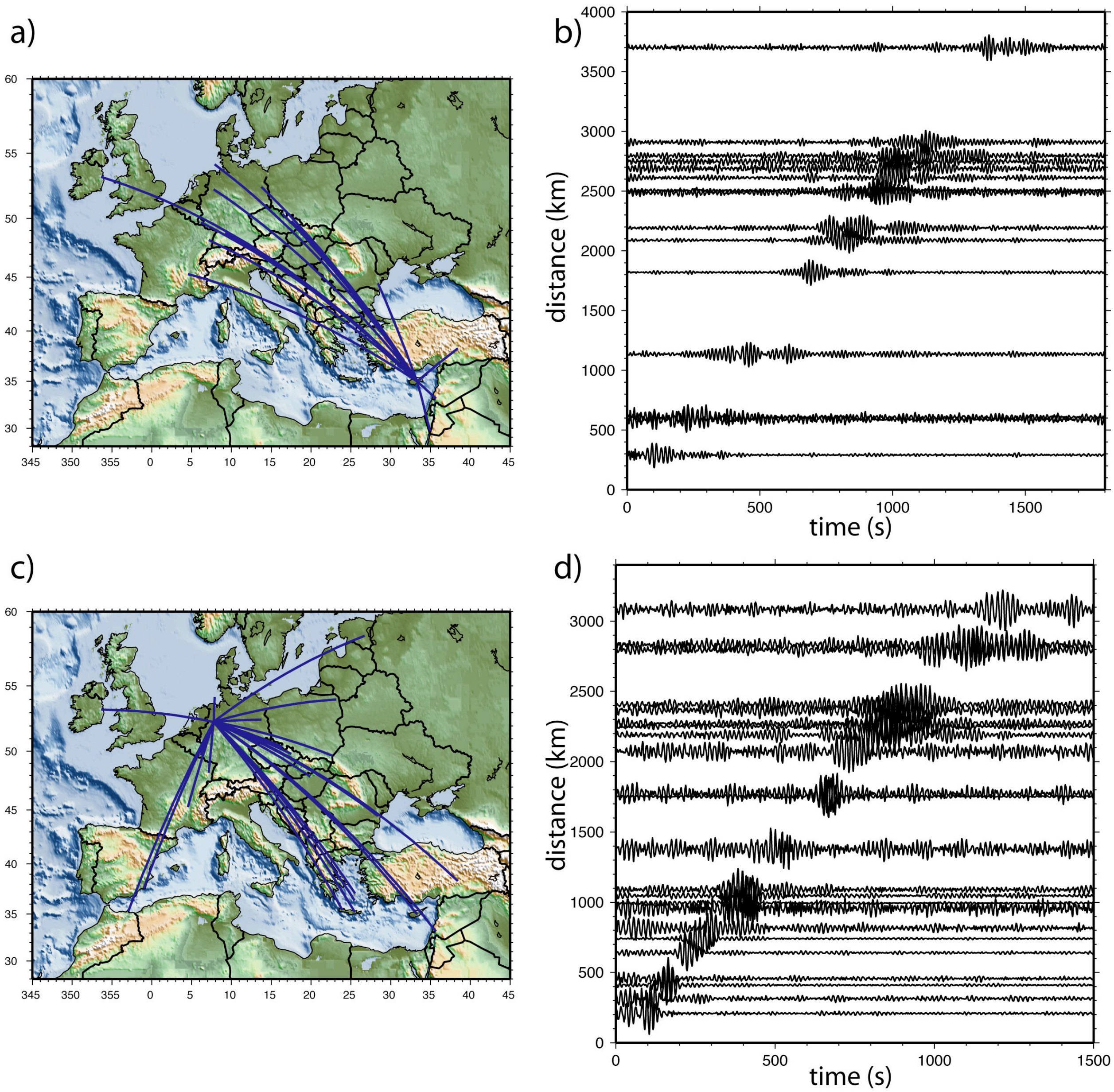

Figure 7. Example receiver gathers (record sections for particular stations) for one-month cross-correlations (Jan. 2004) bandpassed between 10 and 20 sec period for two European stations: CSS (Cyprus) and IBBN (N. Germany). (a) Paths between stations linked to CSS. (b) Receiver gather for station CSS. (c) Paths between stations linked to CSS. (d) Receiver gather for station IBBN. In (b) and (d) only positive cross-correlation lags are shown.