Ambient Noise Tomography in the Western US using Data from the EarthScope/USArray Transportable Array

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Introduction

The teleseismic transmission of seismic surface waves from earthquakes results in a loss of the high frequencies needed to infer information about Earth's crust and uppermost mantle. A recent innovation in seismic imaging based on using long time sequences of ambient seismic noise moves beyond some of the limitations imposed on earthquakebased methods to reveal high resolution information about the crust and uppermost mantle. This method is called Ambient Noise Tomography (ANT) and has been applied predominantly to seismic surface waves. The application of ANT to data from ambitious new deployments of seismic arrays, such as the EarthScope USArray in the United States, has led to the development of large-scale seismic models of the earth's crust and uppermost mantle at unprecedented resolution. In addition, new methods of data analysis and interpretation of ambient noise data that exploit the array nature of the TA are currently under development and hold out the promise for more reliable information about crustal and uppermost mantle anisotropy

The idea of ambient noise tomography

Any mechanism that produces waves that propagate coherently between a pair of seismometers can be used as a basis for seismic tomography. This idea has a long history in seismology, but was resurrected by Lobkis and Weaver (2001) and other researchers in

a series of papers that showed in the laboratory and theoretically that cross-correlations between recordings of diffuse waves at two receiver locations yield the "Green's function" between these positions. The Green's function is a seismic waveform that contains all of the information about wave propagation in the medium between the two stations. Once estimated, traditional seismic methods of tomography then can be applied to the Green's function to recover information about the medium of transport.

The relevance of these results to large-scale earth imaging was not immediately clear because the Earth's ambient noise field, containing as it does energetic microseismic energy, is not diffuse, is probably not homogeneously distributed in azimuth, and its frequency content was poorly understood. Shapiro and Campillo (2004) showed that coherent Rayleigh surface waves can be extracted from the Earth's ambient noise field and that the primary frequency content of the waves lies in the microseismic and "earth hum bands" from about 6 sec to 100 sec period with the highest amplitudes in the microseismic band. Subsequent studies have confirmed that the full Green's function does not emerge from cross-correlating seismic data because the cross-correlations are dominantly surface waves, with Love waves also being observable (Lin et al., 2008a). Nevertheless, the ability to constrain surface wave speeds at periods from 6 to 20 sec, which are sensitive to crustal depths but difficult to measure from teleseismic earthquakes, provided much of the early interest in the method.

Observations of broad-band surface waves

Bensen et al. (2007) presented a primer on ambient noise data processing and provided methods for removing earthquakes and instrumental irregularities from seismograms prior to cross-correlation. They also showed that longer time series (a year or more) homogenize the azimuthal content of ambient noise, that reliable measurements require a station separation of at least two wavelengths, and that uncertainties can be estimated from the temporal repeatability of the measurements.

The production of maps of the speed of Rayleigh or Love waves as a function of frequency is called *surface wave tomography*. Ambient noise tomography (ANT) is the

generation of such maps from inter-station ambient noise cross-correlations. The first ambient noise tomographic images of Rayleigh wave group speeds in the microsseismic band were based on some of the earliest data from the TA in 2004. The results were presented simultaneously by Shapiro et al. (2005) and Sabra et al. (2005) based on one to several months of data in southern California. These studies were followed by a multiplicity of applications around the world including studies in Europe, New Zealand, South Africa, Korea, Japan, Iceland, Canada, Australia, and China in addition to the US where application has focused on the ANSS backbone (e.g., Bensen et al., 2008) and the TA (Moschetti et al., 2007; Lin et al., 2008a) (Figure 1). Both Rayleigh and Love wave dispersion maps are now commonly obtained at periods from 6 sec to 100 sec with the spatial extent of study ranging up to the continental scale (e.g., Bensen et al., 2008) and time series lengths of more than 4 years used in some cases.

ANT is most powerful when applied to large deployments of seismometers, such as the Transportable Array (TA) component of EarthScope/USArray which includes more than 400 broad-band seismometers deployed concurrently with a station separation of about 70 km and is presently sweeping across the US. Lin et al. (2008a) showed that the resolution of ANT applied to EarthScope TA data is better than the inter-station spacing, which is unprecedented over an area the size of the western US. The construction of similar large-scale deployments of seismometers is occurring or planned in China and Europe.

There has remained pockets of concern among seismologists that ambient noise in the Earth does not meet the theoretical conditions on which ANT rests. In particular, the worry has been that the azimuthal inhomogeneity of ambient noise may, at worst, vitiate the method and, at best, generate biased measurements. Studies of the directionality of ambient noise by Stehly et al. (2006) and Yang et al. (2008a) demonstrate that with the use of time series of a year or more in length, ambient noise propagates across a wide range of azimuths although there maybe some preferred directions. Simulations of the observed azimuthal content of ambient noise establish that measurement bias is small relative to other sources of measurement error.

3-D images of Earth's interior

The promise of ANT is not just to reveal the speed of surface waves at different periods (Figure 1), but to use this information to unveil the three-dimensional (3-D) variation of seismic wave speeds in Earth's interior in order to advance knowledge of temperature, composition, and fluid content which hold a key to the understanding of Earth processes. Recent studies based on TA data in the western US, such as that of Yang et al. (2008b), invert ambient noise and earthquake derived information simultaneously to provide 3-D images of the crust and uppermost mantle over large areas in great detail (Figure 2). ANT not only provides better lateral resolution over traditional surface wave methods in regions with good station coverage, but its broad frequency content, which extends to periods below 10 sec, also gives the vertical resolution needed to resolve crustal from mantle structures clearly.

Emerging developments: Wavefront tracking across the TA and anisotropy

Ambient noise tomography predominantly has applied "single-station" methods that interpret group or phase travel times between station-pairs. The close and regular station spacing of the TA, however, allows ambient noise phase fronts to be tracked between a central station and all other stations in the array (Figure 3a,b) giving a phase travel time surface. In this case, at a particular location the gradient of each travel time surface (centered on different stations) is related to the magnitude of the phase speed and the direction of wave propagation. The multiplicity of travel time surfaces centered on different stations greatly beats down uncertainties allowing for clear determination of isotropic (Figure 3c) and azimuthally anisotropic phase speeds (Figure 3d) across the array with attendant uncertainties. We call this method "Eikonal Tomography" (Lin et al., 2008b). The emergence of constraints on azimuthal anisotropy for surface waves from 10 to 30 sec period holds out the promise to produce new information about crustal and uppermost mantle anisotropy across the entire US.

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Related Web Sites

Ambient noise tomography in the US: <u>http://ciei.colorado.edu/ambient_noise</u>

Figure Captions

Figure 1. Example Rayleigh wave group speed map at 8 sec period across the western US determined by ambient noise tomography applied to several years of data from the EarthScope/USArray Transportable Array. Black lines delineate geological provinces. Slow speeds are associated with sedimentary basins (e.g., Central Valley in CA, Salton Trough in CA, Green River Basin in WY), deformed regions (e.g., CA coastal ranges, Olympic Peninsula in northwest WA; Yakima Fold Belt in central WA), and very hot areas (e.g., Yellowstone in WY). Faster speeds are correlated with mountain belts (e.g., Sierra Nevada in CA; Cascade Range in CA, OR, WA; Peninsular Range in southern CA and Baja Mexico), massive flood basalts in OR and WA, and the Colorado Plateau near the Four-Corners region. (Figure courtesy of Morgan Moschetti.)

Figure 2. Images of the 3-D variation of shear wave speed (Vs) in the crust and uppermost mantle determined from ambient noise and earthquake information. (a) Horizontal slice at 100 km depth. (b) Vertical profile underlying the white line at 46°N in (a). Vertically exaggerated surface topography is presented at top and the black line indicates the Moho. In both panels, Vs is presented as the perturbation in percent from the average at each depth across the model. Numerous features are imaged in the crust and mantle. For example, in the mantle the subducting Juan de Fuca and Gorda plates are seen as high Vs beneath N. CA, OR, and WA in both (a) and (b). In (b), the high Vs subducting plate is overlain by low Vs speeds (high temperature and volatile content) beneath active volcanoes in the Cascade Range. (Figure courtesy of Yingjie Yang.)

Figure 3. Example results of wavefield tracking and Eikonal Tomography applied to ambient noise observed across the EarthScope/USArray TA. (a)-(b) Phase travel time surfaces for the 24 sec Rayleigh wave determined from ambient noise tracked across the TA centered on TA stations R06C and F10A, respectively. (c) Phase speed map for the 24 sec Rayleigh wave determined by Eikonal Tomography. (d) Azimuthal anisotropy fast axes for the 24 sec Rayleigh wave phase speeds determined by Eikonal Tomography. (Figure courtesy of Fan-Chi Lin.)





