High resolution surface wave tomography from ambient seismic noise

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submitted to *Science*, December 5, 2004.

Cross-correlating one month of ambient seismic noise recorded at USArray stations in California yields hundreds of short period surface-wave group-speed measurements on inter-station paths. This fundamentally new type of measurement is used to construct tomographic images that reflect the principal geological units within California, with low-speed anomalies corresponding to the main sedimentary basins and high-speed anomalies coincident with the igneous cores of the major mountain ranges. This method promises significant improvements in the resolution and fidelity of crustal images that result from the analysis of surface waves, particularly in the context of emerging dense seismic arrays such as the USArray component of EarthScope.

The aim of ambitious new deployments of seismic arrays, such as the PASSCAL and USArray programs (*1*), is to improve the resolution of images of the Earth's interior by greatly densifying regional- and continental-scale seismic networks. Traditional observational methods in seismology, particularly in the use of surface waves, suffer several significant shortcomings in fully exploiting emerging array data. First, traditional observational methods are based on "ballistic" waves emitted from earthquakes, which constitute only a small fraction of the observed seismogram and emanate from select source regions predominantly near plate boundaries. Second, at observing stations far from source regions, such as most locations within the United States, high frequency information is lost due to intrinsic attenuation and scattering and resolution is degraded by the spatial extent of the wave's sensitivity which expands with path length (*2–4*). For surface waves, this results in lost information about the crust and poor lateral resolution in the mantle. For these and related reasons, surface waves are often an afterthought in the use of seismic array data. This is unfortunate as they provide information complementary to body waves due to sensitivity to shear velocities (useful for seismic hazard assessment and to infer composition and volatile content), the homogeneity of their spatial coverage, and the vertical resolution of genuinely broad-band surface wave dispersion. To move beyond these limitations requires observational methods based on seismic sources other than earthquakes. Fortunately, seismic surface-wave dispersion information can be recovered from ambient seismic noise (*5*) produced by fluctuations in the Earth's atmosphere and oceans (*6–9*). By using new USArray data (*10*), we demonstrate that this method is the much needed alternative to surface wave imaging based on ballistic waves and provides shorter period surface wave dispersion measurements at a higher resolution than traditional methods.

The extraction of deterministic waves from records of ambient noise has been performed successfully in helioseismology (*11*) and acoustics (*12, 13*). Within seismology, the interest in random wavefields was intiated by Aki (*14, 15*). It has also been proposed in exploration seismology to use ambient noise to extract reflections from subsurface interfaces (*16*), but the method enjoyed only limited success (*17*). More recently, cross-correlations of noise sequences within the seismic coda (*18*) and much longer time series of ambient seismic noise (*5*) have been demonstrated to recover surface wave dispersion successfully.

The basic idea of the method is that cross-correlation of a random, isotropic wavefield computed between a pair of receivers will result in a waveform that differs only by an amplitude factor from the Green function between the receivers (*12, 19*). This property should not be surprising, as it is suggested by the fluctuation-dissipation theorem of statistical physics (*20*) which posits a relation between the random fluctuations of a linear system and the system's response to an external force. This concept is widely used in various physical applications and finds its roots in early works on Brownian noise including Einstein's (*21, 22*).

Ambient seismic noise can be considered as a random and isotropic wavefield both because the distribution of the ambient sources responsible for the noise randomizes when averaged over long times and because of scattering from heterogeneities that occurs within the Earth (*23*). Surface-waves are most easily extracted from the noise (*5*) because they dominate the Green function between receivers located at the surface and also because ambient seismic noise in the Earth is excited preferentially by superficial sources, such as oceanic microseisms and atmospheric disturbances (*6–9*). The seismic noise field is, in fact, often not perfectly isotropic and may be dominated by waves arriving from a few principal directions. To reduce the contribution of the most energetic arrivals, we disregard the amplitude completely by correlating only one-bit signals (*18, 24*) prior to the computation of the cross-correlation.

Examples of cross-correlations between pairs of seismic stations in California appear in Fig. 2 (*25*). Cross-correlations between two station pairs (MLAC - PHL, SVD - MLAC) in two short period bands (5 s - 10 s, 10 s - 20 s) are presented using four different one month time series (January, April, July, October 2002). For each station-pair, results from different months are similar to one another and to the results using a whole year of data, but differ between the station-pairs. Thus, the extracted Green functions are stable over time and characterize the path between the stations. In addition, the Green functions extracted by cross-correlating ambient noise sequences are very similar to surface-waves emitted by earthquakes near one receiver observed at the other receiver. This confirms that the cross-correlations approximate Green functions of Rayleigh waves propagating between each pair of stations. This test also establishes that in the period band of interest here (7 s - 20 s) one month of data suffices to extract Rayleigh wave Green functions robustly.

We selected 30 days of continuous 1 sample per second data from 62 USArray stations within California from August and September 2004, removing time sequences following earthquakes larger than magnitude 5.8. Short period surface wave dispersion curves are estimated from the Green functions using frequency-time analysis (*26–28*). The estimated group speed curves are clearly related to variations in the seismic structure between different geological units (Fig. 3). The slowest Rayleigh wave group speeds below 10 s period are observed for paths crossing the large sedimentary basins of the Central Valley and the Imperial Valley. A variation in dispersion characteristics is apparent within the Central Valley, with short period group speeds gradually slowing from the middle of the basin to the south. At longer periods (> 12 s), the measured group speeds clearly delineate the seismically fast core of the Sierra Nevada from the slower Great Basin to the east.

Dispersion measurements between 6 sec and 18 sec period, such as those shown in

Fig. 3, are very difficult to obtain using ballistic waves from earthquakes. Teleseismic arrivals are attenuated below observability at periods shorter than about 15 sec (*27*). Relatively large regional seismicity, therefore, is required and the distribution of the resulting measurements is invariably poor even in regions of moderate seismic activity such as Southern California. Cross-correlating month long time series of ambient seismic noise, therefore, provides entirely new information about the crust of Southern California.

We applied the cross-correlation procedure systematically to the 1891 paths connecting the 62 USArray stations in California with the same measurement procedure used to construct the dispersion curves in Figure 3. We rejected waveforms with low "signal-to-noise" ratios and for paths shorter than two wavelengths. We then measured group speeds at periods of 7.5 s and 15 s from the 5-10 s and 10-20 s pass-bands, resulting in 678 and 891 group speed measurements, respectively (shown in Fig. SM1 in the supplementary materials). Finally, we applied a tomographic inversion (*29*) to these two data sets to obtain group speed maps on a 28 km $\times$ 28 km grid across California (Fig. 4). The maps produced variance reductions of 93% and 76% at 7.5 s and 15 s, respectively, relative to the regional average at each period. To test the robustness of the inversion, we applied the same measurement and inversion procedure to a second month of data. The tomographic maps are remarkably similar. (See Fig. SM2 in the supplementary materials.) The resolution of the resulting images is about the average inter-station distance, approximately 75-100 km across much of each map.

A variety of geological features (*30*) are recognizable in the estimated group-speed dispersion maps (Fig. 4). For the 7.5 s Rayleigh wave, which is mostly sensitive to shallow crustal structures no deeper than about 10 km, the dispersion map displays low-speed anomalies for the principal sedimentary basins in California, including the basins in the Central Valley, the Salton Trough in the Imperial Valley, the Los-Angeles Basin, and the Ventura Basin. Regions consisting mainly of plutonic rocks (e.g., the Sierra Nevada, the Peninsular Ranges, the Great Basin, and the Mojave Desert region) are characterized predominantly by fast group speeds. Somewhat lower speeds are observed in the Mojave Shear Zone and along the Garlock fault. The Coast Ranges, the Transverse Ranges, and the Diablo Range which are mainly composed of sedimentary rocks are characterized by low group speeds, with the exception of the Salinian block located south of Monterey Bay.

For the 15 s Rayleigh wave, sensitive mainly to the middle crust down to depths of about 20 km, two very fast anomalies are observed on the dispersion map, corresponding to the remnants of the Mesozoic volcanic arc: the Sierra Nevada and the Peninsular Ranges composed principally of Cretaceous granitic batholiths. The 15 s map also reveals the contrast between the western and eastern parts of the Sierra Nevada (*31*). The 15 s group speeds are significantly lower in the Great Basin and in the Mojave Desert, indicating that the middle crust in these areas is probably hotter and weaker than in the Sierra Nevada. As at 7.5 s period, very low speeds are observed in the southern and the northern parts of the Central Valley, while in the middle of the valley group speeds are relatively fast. This confirms that the Central Valley is composed of two deep sedimentary basins, the San Joaquin Basin in the south and the Sacramento Basin in the north separated by the Stockton Arch in the middle (*32*) where sediments thin appreciably. Group speeds remain low in the Transverse Ranges, the southern part of Coast Ranges, and the Diablo Range which are composed of sedimentary rocks. Neutral to fast wave speeds are observed for the Salinian block located south of the Monterey Bay. In this area, the 15 s map shows a very clear contrast between the high speed western wall of the San-Andreas fault, composed of plutonic rocks of the Salinian block, and its low-speed eastern wall composed of sedimentary rocks of the Franciscan formation.

These results establish that Rayleigh wave Green functions extracted by cross-correlating long sequences of ambient seismic noise, which is discarded as part of traditional seismic methods, contain entirely new information about the structure of the shallow and middle crust across an extended region of Southern California. Dispersion maps from 7 s to 15 s period at this resolution (∼75-100 km) simply cannot be achieved with traditional methods based on ballistic teleseismic waves. The use of ambient seismic noise as the source for seismic observations addresses the principal shortcomings of traditional surface wave methods. First, the method is particularly advantageous in the context of temporary seismic arrays such as the Transportable Array component of USArray or PASSCAL experiments. Typical temporary installations of 1 - 2 years are guaranteed to return useful interstation dispersion information, whereas traditional methods are based on earthquakes that may or may not occur. Second, the short period dispersion maps produced by the new method provide homogeneously distributed information about shear wave speeds in the crust which are very hard to acquire with traditional methods. Finally, horizontal resolution with traditional earthquake surface wave seismology is low due to long source-receiver paths with azimuthal coverage that is often less than ideal. Resolution is greatly enhanced with the use of ambient noise as the source because wave paths lie between receivers which can be spaced reguarly and much closer to one another than to large earthquakes.

The crust within California has been extensively studied and provides an ideal proving ground for this method. Both in its homogeneity of coverage and in its sensitivity to S-wave speeds, the new method does, however, provide a useful complement to crustal information gained previously from 2-D seismic refraction and reflection profiles in California. As the Transportable Array component of USArray expands into the Pacific Northwest and later moves eastward, the short period dispersion maps and new information about the crust will extend into less studied regions across the entire US. As the

Transportable Array approaches a continental-scale, analysis of surface wave Green functions extracted from ambient seismic noise can be extended to longer periods, thereby providing high-resolution information about the deeper crust and the uppermost mantle.

It may seem initially surprisingly that deterministic information about the Earth's crust can result from correlations of ambient seismic noise. This result, however, is simply a seismological example of a fundamental piece of physics called the fluctuation - dissipation theorem, which reminds us that not all noise is bad. Random fluctuations can, in fact, yield the same information as provided by probing a system with an external force. In seismology, external probing through active seismic sources (e.g., explosions) may be prohibitively expensive and earthquakes are both infrequent and inhomogeneously distributed. In many instances, merely "listening" to ambient noise is a more reliable and economical alternative.

Competing interests statement.

The authors declare that they have no competing financial interests.

References and Notes

1. USArray (www.iris.iris.edu/USArray) is one of the components of the new EarthScope (www.earthscope.org) initiative in the United States. PASSCAL is the Program for the Array Seismic Studies of the Continental Lithosphere (www.iris.edu/about/PASSCAL), a program of the Incorporated Research Institutions for Seismology (IRIS, www.iris.edu).

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34. The data used in this work were obtained from the IRIS Data Management Center. We are also particularly grateful to Mikhail Barmin for the help with the tomographic code and to Peter Goldstein for clarifications about the SAC program. We thank Craig Jones for his very helpful tutorial on the geology of California and Roger Maynard, Ludovic Margerin, Eric Larose, Bart van Tiggelen, Richard Weaver, and Oleg Lobkis for helpful discussions.

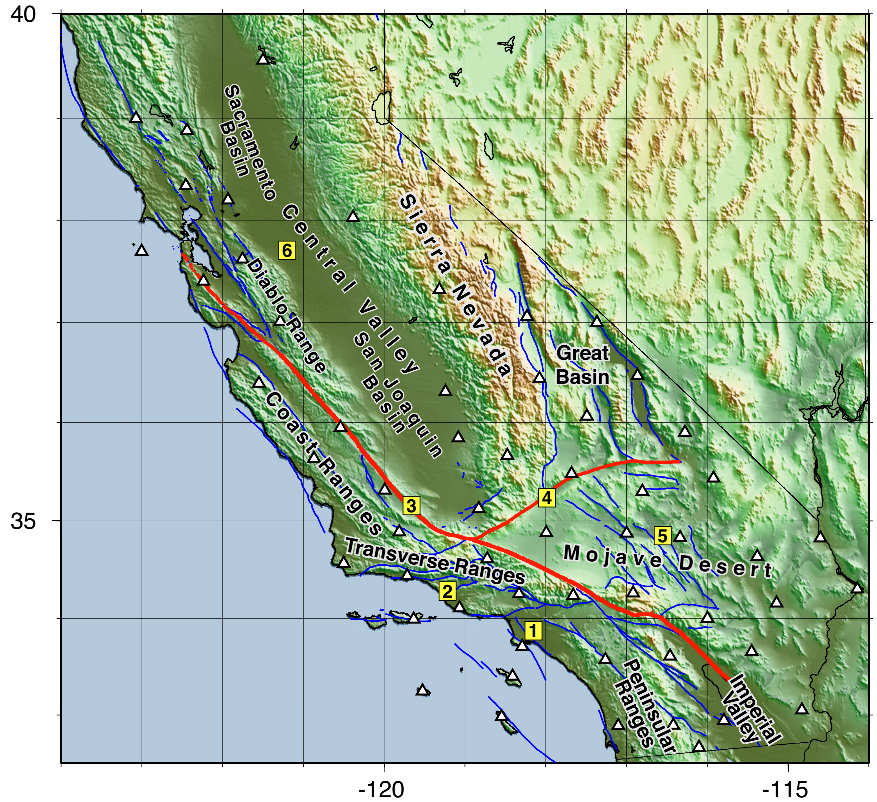

Figure 1: **Reference map showing the locations of principal geographical and geological features discussed in the test.** White triangles show the locations of the USArray stations used in this study (5 of the of 62 stations are located north of 40N and are not shown in this map). Blue and red solid lines show locations of known active faults. Yellow rectangles with digits indicate the following features: (1) Los Angeles Basin; (2) Ventura Basin; (3) San Andreas fault; (4) Garlock fault; (5) Mojave shear zone; (6) Stockton Arch.

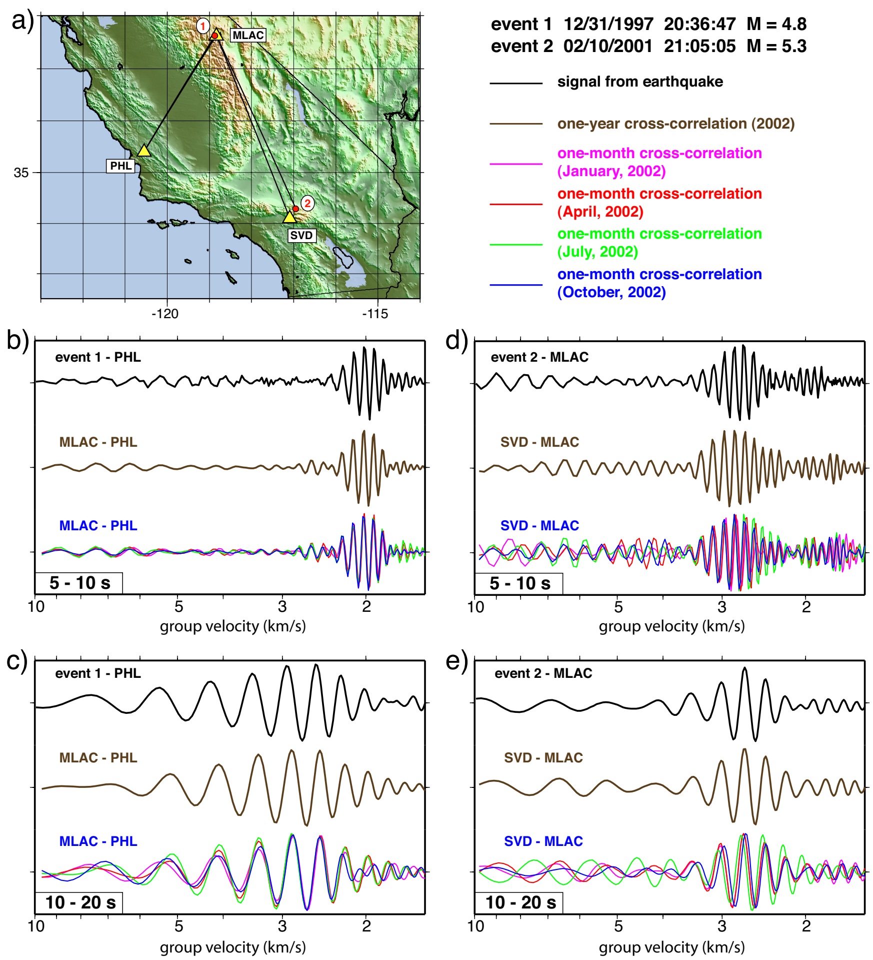

Figure 2: **Waveforms emerging from cross-correlations of ambient seismic noise compared with Rayleigh waves excited by earthquakes.** (a) Map showing locations of three TriNet seismic stations (yellow triangles) and two earthquakes (red circles). (b) Comparison of waves propagating between stations MLAC and PHL, bandpassed between 5 and 10 s. The upper trace shows the signal emitted by an earthquake near MLAC observed at PHL, the middle trace shows the cross-correlation from one year of ambient seismic noise, and the lower traces show cross-correlations from four different months of noise. Noise records were band-passed between 5 and 10 s. The spectrum of the earthquake-emitted signal was re-normalized to make it similar to the spectrum of the waveforms emerging from the ambient noise. (c) Similar to (b), but with the bandpass filter between 10 s and 20 s. (d) Similar to (b), but between stations SVD and MLAC. The earthquake is near SVD observed at MLAC. (e) Similar to (d), but with the bandpass filter between 10 s and 20 s.

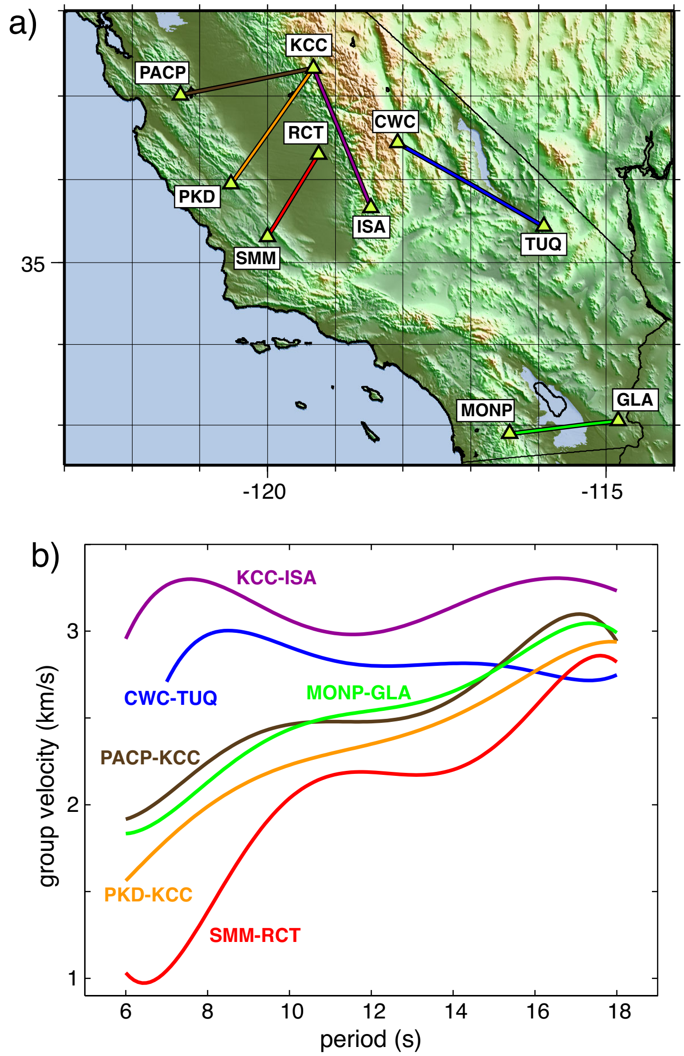

Figure 3: **Group speed curves measured in different parts of California by cross-correlating 30 days of ambient noise between USArray stations.** (a) Map showing the stations locations and inter-station paths. (b) Group speed dispersion curves between periods of 6 s and 18 s.

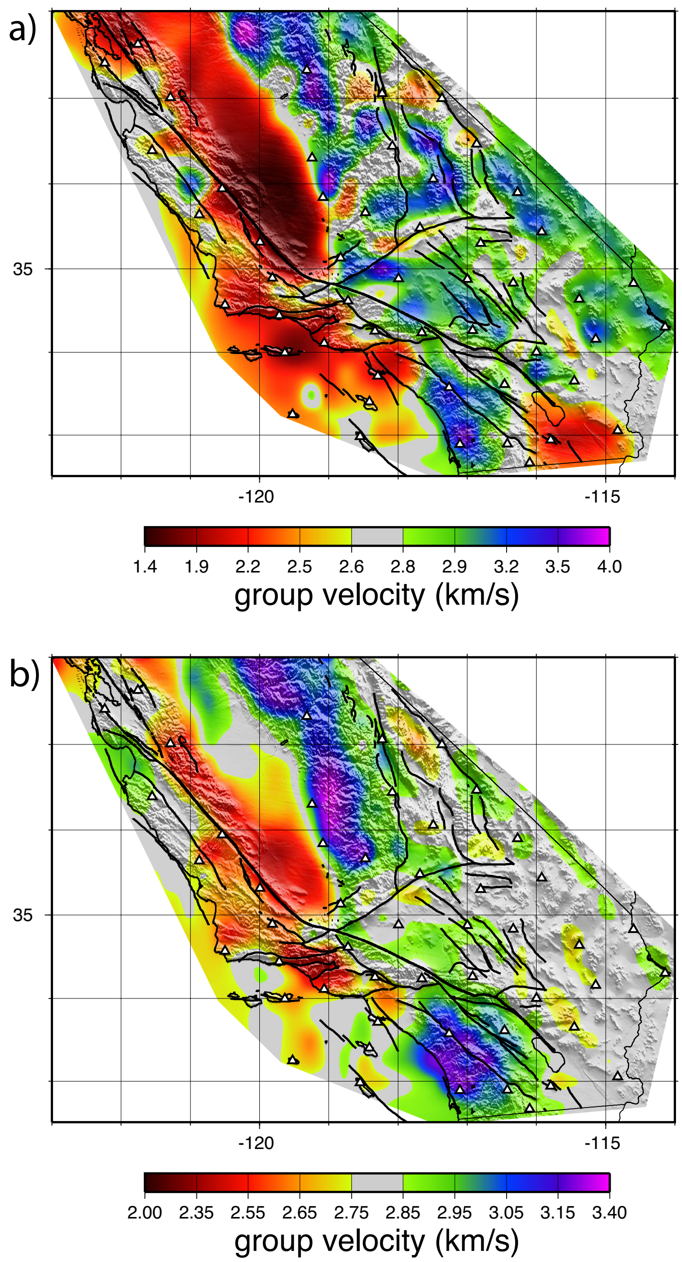

Figure 4: **Group speed maps constructed by cross-correlating 30 days of ambient noise between USArray stations.** (a) 7.5 s period Rayleigh waves. (b) 15 s period Rayleigh waves. Black solid lines show known active faults. White triangles show locations of USArray stations used in this study.