USING SEISMIC AMBIENT NOISE TO IMAGE AND TO MONITOR THE SOLID EARTH

Michel Campillo and Philippe Roux
Observatoire de Grenoble
Université Joseph Fourier and CNRS
BP 53, 38041 Grenoble, France

Nikolai M. Shapiro
Institut de Physique du Globe de Paris
4 place Jussieu, 75252 Paris, France

USING SEISMIC AMBIENT NOISE TO IMAGE AND TO MONITOR THE SOLID EARTH

Definition:

Seismic noise: permanent motion of the Earth surface that is not related to earthquakes or specific controlled sources.

Introduction

Traditional observational methods in seismology are based on earthquake records. It results in two main shortcomings. First, most techniques are based on waves emitted by earthquakes that occurred only in geologically active areas, mainly plate boundaries. This results in a limited resolution in all other areas where earthquakes are not present. Second, the repetition of earthquakes is rare, preventing the study continuous changes within active structures such as volcanoes or faults.

Also at smaller scales in the context of geophysics prospecting, the resolution is limited by the number and power of sources making it difficult to image large areas and/or deep structures. Similarly, reproducible sources are necessary for time-lapse monitoring leading to long-duration surveys that are difficult to achieve.

Nowadays, the seismic networks are producing continuous recordings of the ground motion. These huge amounts of data consist mostly of so called seismic noise, a permanent vibration of the Earth due to natural or industrial sources. Passive seismic tomography is based on the extraction of the coherent contribution to the seismic field from the cross-correlation of seismic noise between station pairs.

As described in many studies where noise has been used to obtain the Green's function between receivers, coherent waves are extracted from noise signals even if, at first sight, this coherent signal appears deeply buried in the local incoherent seismic noise. Recent studies on passive seismic processing have focused on two applications, the noise-extracted Green's functions associated to surface waves leads to subsurface imaging on scales ranging from thousands of kilometres to very short distances; on the other hand, even when the Green's function is not satisfactorily reconstructed from seismic ambient noise, it has been shown that seismic monitoring is feasible using the scattered waves of the noise-correlation function.

Theoretical basis for the interpretation of noise records at two stations.

Passive seismology is an alternative way of probing the Earth's interior using noise records only. The main idea is to consider seismic noise as a wave field produced by randomly and homogeneously distributed sources when averaged over long time series. In this particular case, cross-correlation between two stations yields the Green's function between these two points. In the case of a uniform spatial distribution of noise sources, the cross-correlation of noise records converges to the complete Green's function of the medium, including all reflection, scattering and propagation modes. However, in the case of the Earth, most of ambient seismic noise is generated by atmospheric and oceanic forcing at the surface. Therefore, the surface wave part of the Green's function is most easily extracted from the noise cross-correlations. Note that the surface waves are the largest contribution of the Earth response between two points at the surface.

Historically speaking, helioseismology was the first field where ambient-noise cross-correlation performed from recordings of the Sun's surface random motion was used to retrieve time-distance information on the solar surface. More recently, a seminal paper was published by Weaver and Lobkis (2001) that showed how, at the laboratory scale, diffuse thermal noise recorded and cross-correlated at two transducers fastened to one face of an aluminium sample provided the complete Green's function between these two points. This result was generalized to the case where randomization is not produced by the distribution of sources, but is provided by multiple scattering that takes place in heterogeneous media.

By summing the contributions of all sources to the correlation, it has been shown numerically that the correlation contains the causal and acausal Green's function of the medium. Cases of non-reciprocal (e.g. in the presence of a flow) or inelastic media have also been theoretically investigated. Derode et al. *(2003)* proposed to interpret the Green's function reconstruction in terms of a time-reversal analogy that makes it clear that the convergence of the noise correlation function towards the Green's function is bonded to the stationary phase theorem. For the more general problem of elastic waves, one could summarize that the Green's function reconstruction depends on the equipartition condition of the different components of the elastic field. In other words, the emergence of the Green's function is effective after a sufficient self-averaging process that is provided by random spatial distribution of the noise sources when considering long time series as well as scattering (e.g Gouedard et al. 2008 and references herein).

Applications in seismology

For the first time, Shapiro and Campillo (2004) reconstructed the surface wave part of the Earth response by correlating seismic noise at stations separated by distances of hundreds to thousands of kilometres, and measured their dispersion curves at periods ranging from 5 to about 150 seconds. Then, a first application of passive seismic imaging in California (e.g., Shapiro et al., 2005; Sabra et al., 2005) appeared to provide a much greater spatial accuracy than for usual active techniques. More recently, the feasibility of using the noise cross-correlations to monitor continuous changes within volcanoes and active faults was demonstrated (e.g., Brenguier, 2008a,b). These results demonstrated a great potential of using seismic noise to study the Earth interior at different scales in space and time. At the same time, the feasibility of both noise-based seismic imaging and monitoring in every particular case depends on spatio-temporal properties of the available noise wavefield. Therefore, a logical initial step for most of noise-based studies is to characterize the distribution of noise sources. Also, in many cases, knowledge of the distribution of the noise sources can bring very important information about the coupling between the Solid Earth with the Ocean and the Atmosphere. So far, we can identify three main types of existing seismological applications related to noise correlations: (1) studies of spatio-temporal distribution of seismic noise sources, (2) noise-based seismic imaging, and (3) noise-based seismic monitoring.

Noise source origin and distribution

Distribution of noise sources strongly depends on the spectral range under consideration. At high frequencies (> 1Hz) the noise is strongly dominated by local sources that may have very different origins and are often anthropogenic. At these scales, the properties of the noise wavefield should be studied separately for every particular case and no reasonable generalisation can be done. At longer periods, noise is dominated by natural sources. In particular, it is well established that two main picks in the seismic noise spectra in so-called microseismic band (1-20 s) are related to forcing from oceanic gravity waves. It has been also argued that at periods longer than 20s, the oceanic gravity and infragravity waves play a major role in the seismic noise excitation. The interaction between these oceanic waves and the solid Earth is governed by a complex non-linear mechanism (Longuet-Higgins, 1950) and, as a result, the noise excitation depends on many factors such as the intensity of the oceanic waves but also the intensity of their interferences as well as the seafloor topography (e.g., Kedar et al., 2008). Overall, the generation of seismic noise is expected to be strongly modulated by strong oceanic storms and, therefore, to have a clear seasonal and non-random pattern.

Seismic noise in the microseismic spectral band is dominated by fundamental mode surface waves. It is currently debated whether the surface wave component of microseisms is generated primarily along coastlines or if it is also generated in deep-sea areas. Inhomogeneous distribution and seasonality of microseismic noise sources is clearly revealed by the amplitude of the Rayleigh wave reconstructed in noise cross-correlations (e.g., Stehly et al., 2006) as shown in Figure 1. At the same time, body waves were detected in the secondary microseismic band and can be sometimes associated with specific storms. Figure 2 shows that sources of microseismic P-waves are located in specific areas in deep ocean and exhibit strong seasonality as determined from the analysis of records by dense seismic networks (Landes et al., 2010).

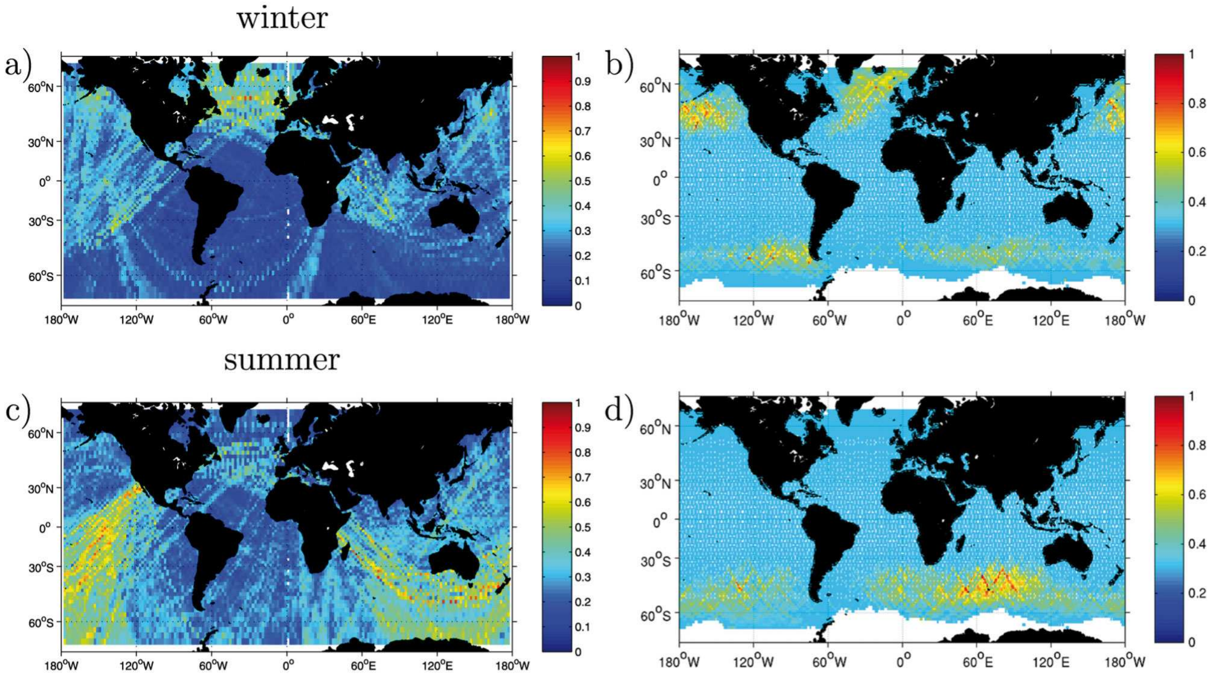
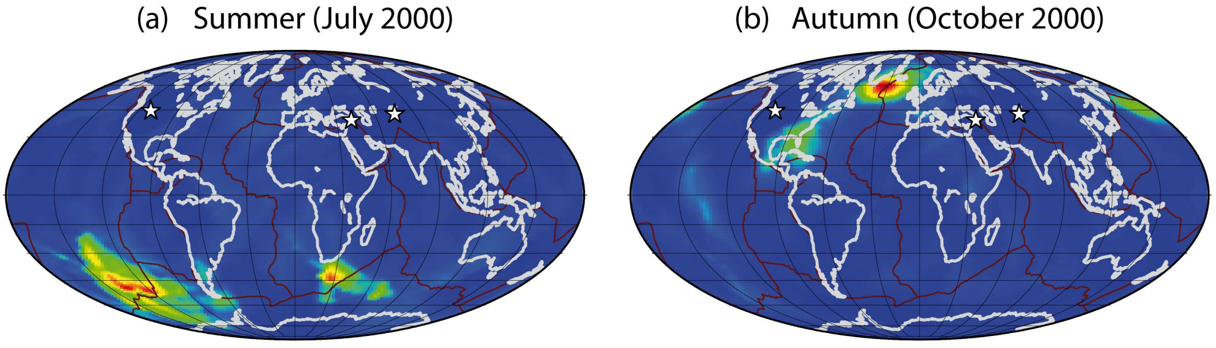
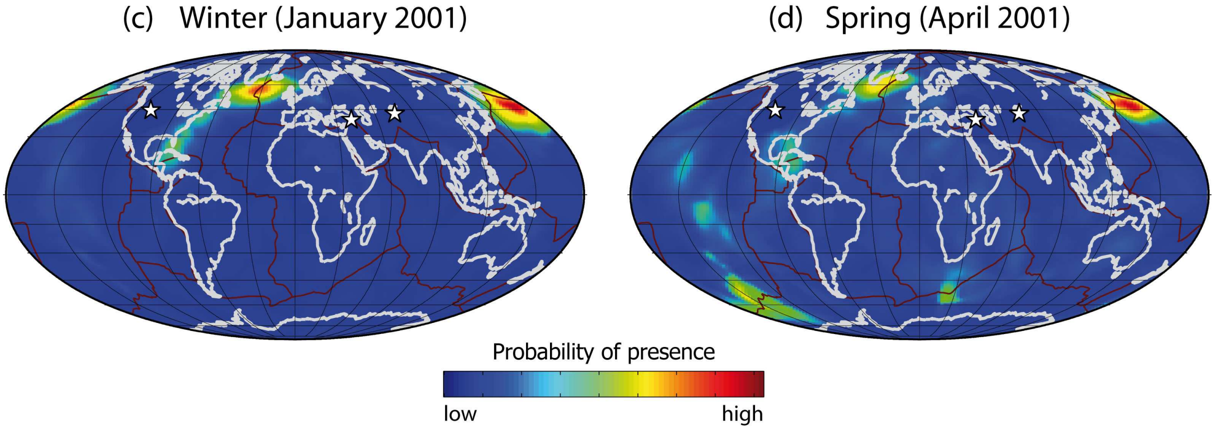


Figure 1: Comparison between seasonal variations of the location of seismic noise sources and significant wave height. (a) and (c) Geographical distribution of the apparent source of the Rayleigh waves detected in the 10–20 s noise cross correlations during the winter and the summer, respectively. (b) and (d) Global distribution of the square of wave height measured by TOPEX/Poseidon during the winter and the summer, respectively. (From Stehly et al., 2006)



(a) Summer (July 2000)

(b) Autumn (October 2000)



(c) Winter (January 2001)

(d) Spring (April 2001)

Figure 2: Seasonal variation of the location of P-wave seismic noise sources in the secondary microseismic band (0.1-0.3 Hz) determined from the analysis of records at the three seismic networks indicated with white stars (From Landes et al., 2010).

Noise based seismic imaging

Numerous studies has demonstrated that, when considered over sufficiently long times, the noise sources become sufficiently well distributed over the Earth’s surface and that dispersion curves of fundamental mode surface waves can be reliably measured from correlations of seismic noise at periods between 5 and 50 s for most of inter-station directions. This led to the fast development during recent years of the ambient noise surface wave tomography. It consists of computing cross-correlations between vertical and horizontal components for all available station pairs followed by measuring group and phase velocity dispersion curves of Rayleigh and Love waves (e.g., Bensen et al., 2007). This dispersion curves are then regionalized (e.g., Lin et al., 2009) and inverted to obtain three-dimensional distribution of shear velocities in the crust and the uppermost mantle. After first results obtained in southern California (Shapiro et al., 2005; Sabra et al., 2005), this method has been applied with many regional seismological networks (e.g., Yao et al., 2006; Lin et al., 2007; Yang et al., 2008a). At smaller scales, it can be used to study shallow parts of volcanic complexes (e.g., Brenguier et al., 2007). The ambient noise surface wave tomography is especially advantageous in context of dense continent-scale broadband seismic networks such as available in US (e.g., Moschetti et al., 2007; Yang et al., 2008b) and Europe (e.g., Stehly et al., 2009). At these scales, noise-based imaging can be used to obtain high-resolution information about the crustal and the upper mantle structure including seismic anisotropy (e.g., Moschetti et al., 2010) and can be easily combined with earthquake-based measurements to extend the resolution to larger depths (e.g., Yang et al., 2008b). An example of results obtained from combined noise and earthquakes based surface wave tomography in western US is shown in Figure 3.

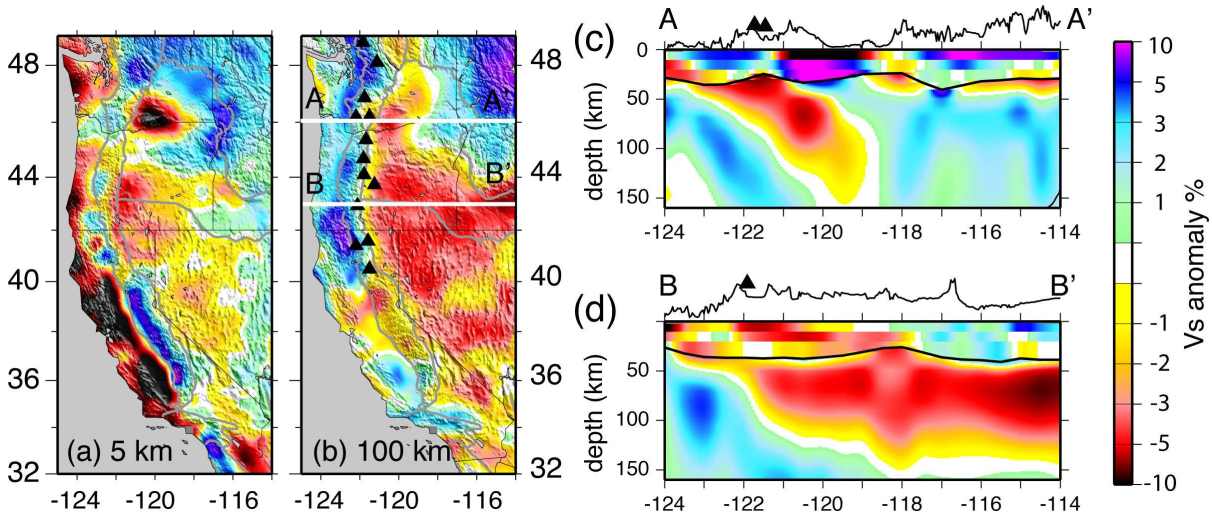


Figure 3. Shear-velocity structure of the crust and the upper mantle obtained from the inversion of the USArray data. (a) and (b) Horizontal cross-sections at depths of 5 and 100 km. (c) and (d) Vertical cross-sections along profiles delineated by the white lines in (b). Black lines outline the Moho. Topography is superimposed above individual cross sections. The black triangles represent active volcanoes in the Cascade Range. (From Yang et al., 2008b).

Noise based monitoring

One of the advantages of using continuous noise records to characterize the earth materials is that a measurement can easily be repeated. This led recently to the idea of a continuous monitoring of the crust based on the measurements of wave speed variations. The principle is to apply a differential measurement to correlation functions, considered as virtual seismograms. The technique developed for repeated earthquakes (doublets), proposed by Poupinet et al., 1984, can be used with correlation functions. In a seismogram, or a correlation function, the delay accumulates linearly with the lapse time when the medium undergoes a homogeneous wave speed change and a slight change can be detected more easily when considering late arrivals. It was therefore reasonable, and often necessary, to use coda waves for the measurements of temporal changes. Noise based monitoring relies on the autocorrelation or cross-correlation of seismic noise records (Sens-Schönfelder and Wegler, 2006, Brenguier et al., 2008a,b). When data from a network is available, using cross-correlation take advantage of the number of pairs with respect to the number of stations. It is worth noting that the use of the coda of the correlation functions is also justified by the fact that its sensitivity to changes in the origin of the seismic noise is much smaller than the sensitivity of the direct waves. Several authors noted that an anisotropic distribution of sources leads to small errors in the arrival time of the direct waves, which can be evaluated quantitatively (e.g. Weaver at al., 2008). While in most of the cases, they are acceptable for imaging, they can be larger that the level of precision required when investigating temporal changes. The issue of the nature of the tail (coda) of the cross-correlation function is therefore fundamental and was analyzed by Stehly et al. (2008). These authors showed that it contains at least partially the coda of the Green function, i.e. physical arrivals which kinematics is controlled by the wave speeds of the medium. It can therefore be used for monitoring temporal changes. As an illustration of the capability of this approach, we present in Figure 4 a measure of the average wave speed change during a period of 6 years in the region of Parkfield, California. Two main events occurred in this region during the period of study: the 2003 San Simeon and 2004 Parkfield earthquakes. In both cases, noise based monitoring indicates a co-seismic speed drop. The measured relative variations of velocity before de San Simeon earthquake are as small as 10-4. The changes of velocity associated with earthquakes are associated with at least two different physical mechanisms: (i) the damage induced by the strong ground motions in shallow layers and fault zone, as illustrated by the co-seismic effect of the distant San Simeon event, and (ii) co-seismic bulk stress change followed by the post-seismic relaxation, as shown with the long term evolution after the local Parkfield event, similar in shape to the deformation measured with GPS.

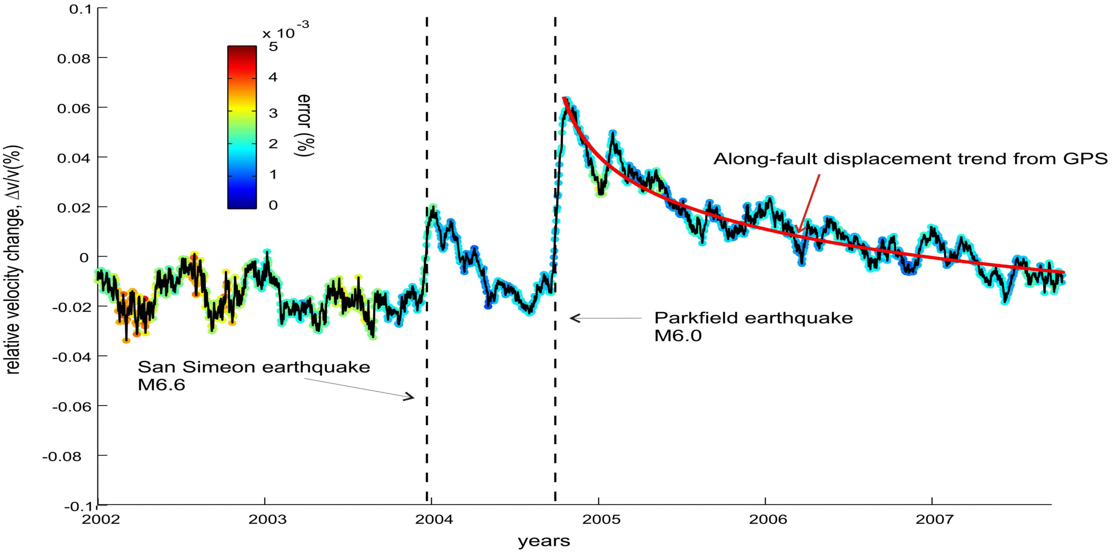


Figure 4: Relative seismic velocity change during 6 years measured from continuous noise correlations in Parkfield. The dashed lines indicated two major earthquakes: the San Simeon event that occurred 80 km from Parkfield and the local Parkfield event (modified from Brenguier et al. 2008b)

Summary

Continuous recordings of the Earth surface motion by modern seismological networks contain a wealth of information on the structure of the planet and on its temporal evolution. Recent developments shown here make it possible to image the lithosphere with noise only and to detect temporal changes related to inner deformations.

Bibliography

Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang, Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, Geophys. J. Int., 169, 1239-1260, doi: 10.1111/j.1365-246X.2007.03374.x, 2007.

Brenguier, F., N.M. Shapiro, M. Campillo, A. Nercessian, and V. Ferrazzini, 3-D surface wave tomography of the Piton de la Fournaise volcano using seismic noise correlations, Geophys. Res. Lett., 34, L02305, doi:10.1029/2006GL028586, 2007.

Brenguier, F., N. Shapiro, M. Campillo, V.Ferrazzini, Z Duputel, O Coutant and A. Nercessian, Toward Forecasting Volcanic Eruptions using Seismic Noise Nature Geoscience 1 Issue: 2 Pages: 126-130, 2008a.

Brenguier F., M. Campillo,C. Hadziioannou, N.M. Shapiro, R.M. Nadeau, E. Larose, Postseismic relaxation along the San Andreas fault in the Parkfield area investigated with continuous seismological observations SCIENCE Volume: 321 Issue: 5895 Pages: 1478-1481, 2008b

Derode ,A., E. Larose, M. Tanter, J. de Rosny, A. Tourin, M. Campillo and M. Fink, Recovering the Green's function from field-field correlations in an open scattering medium, Journal of the Acoustical Society of America, 113, 2973-2976, 2003.

Gouédard, P., L. Stehly, F. Brenguier, M. Campillo, Y. Colin de Verdière, E. Larose, L. Margerin, P. Roux, F. J. Sanchez-Sesma, N. M. Shapiro and R. L. Weaver: Cross-correlation of random fields: mathematical approach and applications, Geophysical Prospecting 56, 375-393, 2008.

Kedar, S., M. Longuet-Higgins, F. Webb, N. Graham, R. Clayton, and C. Jones, The origin of deep ocean microseisms in the North Atlantic Ocean, Royal Society of London Proceedings Series A, 464, 777-793, doi:10.1098/rspa.2007.0277, 2008.

Landes, M., F. Hubans, N. M. Shapiro, A. Paul, and M. Campillo, Origin of deep ocean microseims by using teleseismic body waves, J. Geophys. Res., doi:10.1029/2009JB006918, 2010.

Lin, F., M.H. Ritzwoller, J. Townend, M. Savage, S. Bannister, Ambient noise Rayleigh wave tomography of New Zealand, Geophys. J. Int., doi:10.1111/j.1365-246X.2007.03414.x, 2007.

Lin, F.-C., M.H. Ritzwoller, and R. Snieder, Eikonal Tomography: Surface wave tomography by phase-front tracking across a regional broad-band seismic array, Geophys. J. Int., 177(3), 1091-1110, 2009.

Longuet-Higgins, M. S., A Theory of the Origin of Microseisms, Royal Society of London Philosophical Transactions Series A, 243, 1-35, 1950.

Moschetti, M.P., M.H. Ritzwoller, and N.M. Shapiro, Surface wave tomography of the western United States from ambient seismic noise: Rayleigh wave group velocity maps, Geochem., Geophys., Geosys., 8, Q08010, doi:10.1029/2007GC001655., 2007.

Moschetti, M.P., M.H. Ritzwoller, and F.C. Lin, Seismic evidence for widespread crustal deformation caused by extension in the western USA, Nature, in press.

Poupinet, G., Ellsworth, W. L. & Frechet, J. Monitoring velocity variations in the crust using earthquake doublets: An application to the Calaveras Fault, California, J. Geophys. Res., 89, 5719–5731, 1984.

Sabra, K. G., Gerstoft, P., Roux, P., Kuperman,W. A. & Fehler, M. C. Extracting time domain Green's function estimates from ambient seismic noise. Geophys. Res. Lett. 32, L03310, 2005.

Sens-Schönfelder, C. &Wegler, U. Passive image interferometry and seasonal variations of seismic velocities at Merapi Volcano, Indonesia. Geophys. Res. Lett. 33, L21302, 2006.

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. Campillo, L. Stehly and M. Ritzwoller, High Resolution Surface Wave Tomography from Ambient Seismic Noise, Science, 307, 1615-1618, 2005.

Stehly, L., M. Campillo, B. Froment and R.L. Weaver, Reconstructing Green's function by correlation of the coda of the correlation (C3) of ambient seismic noise, J. Geophys. Res., 113, B11306, 2008.

Stehly, L., B. Fry, M. Campillo, N.M. Shapiro, J. Guilbert, L. Boschi, and D. Giardini, Tomography of the Alpine region from observations of seismic ambient noise, Geophys. J. Int., 178, 338-350, 2009.

Weaver, R. L. and O. I. Lobkis, Ultrasonics without a source: thermal fluctuation correlations at MHz frequencies, Phys. Rev. Lett., 87(13), 134301, doi:10.1103/PhysRevLett.87.134301, 2001.

Weaver, R.L., B. Froment, M. Campillo, On the correlation of non-isotropically distributed ballistic scalar diffuse waves, Journal of the Acoustical Society of America, 1817-1826, 2009.

Yang, Y., A. Li, and M.H. Ritzwoller, Crustal and uppermost mantle structure in southern Africa revealed from ambient noise and teleseismic tomography, Geophys. J. Int., doi:10.1111/j.1365-246X.2008.03779.x, 2008a.

Yang, Y., M.H. Ritzwoller, F.-C. Lin, M.P. Moschetti, and N.M. Shapiro, The structure of the crust and uppermost mantle beneath the western US revealed by ambient noise and earthquake tomography, J. Geophys. Res., 113, B12310, doi:10.1029/2008JB005833, 2008b.

Yao, H., van der Hilst, R.D. & de Hoop, M.V., Surface-wave array tomography in SE Tibet from ambiant seismic noise and two-station analysis – I. Phase velocity maps, Geophys. J. Int., 166, 732–744, 2006.