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Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise

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[1] We demonstrate that the coherent information about the Earth structure can be extracted from the ambient seismic noise. We compute cross-correlations of vertical component records of several days of seismic noise at different pairs of stations separated by distances from about one hundred to more than two thousand kilometers. Coherent broadband dispersive wavetrains clearly emerge with group velocities similar to those predicted from the global Rayleigh-wave tomographic maps that have been constrained using ballistic surface waves. Those results show that coherent Rayleigh waves can be extracted from the ambient seismic noise and that their dispersion characteristics can be measured in a broad range of periods. This provides a source for new types of surface-wave measurements that can be obtained for numerous paths that could not be sampled with the ballistic waves and, therefore, can significantly improve the resolution of seismic images.

INDEX TERMS: 7255 Seismology: Surface waves and free oscillations; 7260 Seismology: Theory and modeling; 7294 Seismology: Instruments and techniques; 8180 Tectonophysics: Tomography. **Citation:** 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.

1. Introduction

[2] Seismic imaging has been traditionally based on direct waves that are emitted by seismic sources such as explosions or earthquakes. Those ballistic waves have been used to measure travel times of the body waves, dispersion curves of the surface waves and frequencies of the Earth's normal modes. Inversion of those measurements provided a fundamental information about the Earth's interior and allowed to understand the Earth's structure both in terms of its spherically symmetric stratification and in terms of three-dimensional and anisotropic variations of seismic properties.

[3] Further increasing of the resolution of seismic images is mostly limited by the inhomogeneous distribution of seismic sources and receivers that still impose some fundamental limitations on the resolution of seismic measurements from the ballistic waves. In this paper we concentrate on seismic surface-waves that are one of main sources of information about the structure of the Earth's crust and upper mantle. Measurements made from direct surface waves have several limitations. First, the direct surface waves mostly sample only a few preferential directions while many other directions of propagation remain unsampled. Second, inversions of the ballistic surface waves require some information about the source that is not always known with a sufficient accuracy. Third, the measurements made with the teleseismic surface waves provide averages values over extended areas [e.g., *Nolet and Dahlen*, 2000; *Spetzler et al.*, 2002] that limits the resolution of resulting seismic images. Fourth, it is difficult to make short-period measurements from teleseismic surface-waves because the heterogeneity results in the simultaneous arrivals of waves with different paths.

2. Cross-Correlations of Random Wavefields

[4] Recent developments in acoustics [e.g., *Weaver and Lobkis*, 2001a, 2001b; *Derode et al.*, 2003] and seismology [*Campillo and Paul*, 2003] suggest an alternative method to measure the elastic response of the Earth by extracting the Green function from the diffuse or random wavefields. Contrary to ballistic waves, fully diffuse wavefields are composed of waves with random amplitudes and phases but propagating in all possible directions and, therefore, contain the information about any possible path that can be extracted by computing cross-correlations between pairs of receivers. A simple demonstration of this property is based on a modal representation of a diffuse wavefield inside an elastic body (the Earth in our case) [*Weaver and Lobkis*, 2001b]:

$$\phi(x,t) = \sum_n a_n u_n(x) e^{i\omega_n t} \tag{1}$$

where x is position, t is time, u_n and ω_n are eigenfunctions and eigenfrequencies of the real Earth, and a_n are modal excitation functions. An important property of the diffuse field is that the modal amplitudes are uncorrelated random variables:

$$\langle a_n a_m^* \rangle = \delta_{nm} F(\omega_n) \tag{2}$$

where $F(\omega)$ is the spectral energy density. Because the cross-terms disappear in average due to equation (2), the correlation between the fields at locations x and y becomes simply:

$$C(x,y,\tau) = \sum_n F(\omega_n) u_n(x) u_n(y) e^{-i\omega_n \tau} \tag{3}$$

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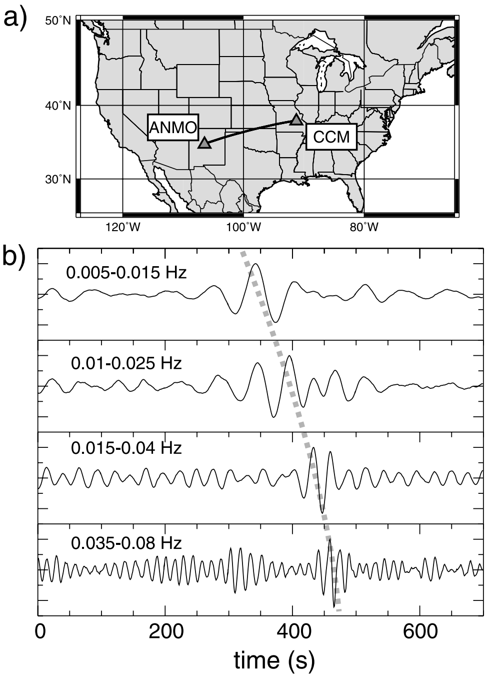

Figure 1. (a) Map showing the station location. (b) Cross-correlations of vertical-component records bandpassed with different filters as indicated in top left corners of each frame. Gray dotted line emphasizes the dispersion of the emerging signal.

The expression equation (3) differs only by an amplitude factor F from an actual Green function between points x and y. This result reminds of the fluctuation-dissipation theorem [*van Tiggelen*, 2003]. Its very important implication is that the Green function between two locations (or at least, the arrival times of the different wave-trains) can be extracted from the diffuse field with a simple field-to-field correlation taken over sufficiently long time.

[5] Extraction of the Green functions from the diffuse wavefield has been successfully applied in helioseismology [e.g., *Duvall et al.*, 1993; *Kosovichev et al.*, 2000; *Rickett and Claerbaut*, 2000], in ultrasonics [e.g., *Weaver and Lobkis*, 2001a, 2001b; *Derode et al.*, 2003], and in marine acoustics [*Roux et al.*, 2003]. In seismology, much attention has been payed to the seismic coda that is created as a result of multiple scattering on the small-scale heterogeneities within the Earth [e.g., *Aki and Chouet*, 1975]. Traditionally, it has been used to extract average statistical properties of the Earth either by interpretations of the envelopes of seismograms based on the radiative transfer theory [e.g., *Abubakirov and Gusev*, 1990; *Hoshiba*, 1991; *Ryzhik et al.*, 1996; *Sato and Fehler*, 1998; *Margerin et al.*, 1999] or by the coda-wave interferometry [e.g., *Cowan et al.*, 2002; *Snieder et al.*, 2002]. The diffuse character of the seismic coda has been explored by [*Hennino et al.*, 2001] by investigating the property of mode equipartition [*Weaver*, 1982] through the observation of the stabilization of the ratio of S- and P-wave energies in the coda of Mexican earthquakes. Recently, the deterministic surface-wave Green functions has been extracted by the correlation of records of seismic coda of regional earthquakes in Mexico by *Campillo and Paul* [2003].

3. Application to the Ambient Seismic Noise

[6] Here, we report results of application of the field-to-field correlation technique to records of the ambient seismic noise that is exited by shallow sources such as ocean microseisms [e.g., *Friedrich et al.*, 1998] and atmospheric perturbations [e.g., *Lognonne et al.*, 1998; *Tanimoto*, 1999]. When taken over long times, the distribution of the ambient sources randomizes and the seismic noise can be considered as a random field satisfying equations (1) and (2). Therefore, even if this randomizing mechanism is different from the multiple scattering that randomizes the seismic coda, we can still expect that the deterministic Green functions can be extracted from the ambient seismic noise. Moreover, using the noise instead of the coda has the very significant advantage that the noise does not depend on the earthquake occurrence and can be recorded in any location almost continuously.

[7] To test if the Green functions can be extracted from the ambient seismic noise, we selected a relatively quiescent period (01/01/2002-02/08/2002) during which there was no large earthquake ($M \geq 7$) in the world and downloaded all available continuous vertical component records at stations ANMO and CCM (Figure 1a) and used them to compute cross-correlations in different period bands. Because the amplitude of the ambient seismic noise can vary by a few orders of magnitude, a simple cross-correlation between noise records at two stations would strongly overweight the most energetic parts of the noise. Therefore, we disregarded the amplitude completely by considering only one-bit signals [*Campillo and Paul*, 2003]. Figure 1b shows that coherent wavetrains emerge at all periods. Moreover, the emerging signal is dispersive as expected for Rayleigh waves inside the Earth, i.e., the long periods arrive before the short periods. To compare the dispersion characteristics of the emerging signal with those that can be measured for the same path from ballistic waves we computed a broadband (0.008–0.07 Hz) cross-correlation and applied to it a frequency-time analysis of *Levshin et al.* [1989] to measure its group-velocity dispersion curve. The result of this analysis between stations ANMO and CCM is shown in Figure 2b and is compared with the dispersion curve predicted by ray-tracing through the global group velocity maps of *Ritzwoller et al.* [2002] constructed from ballistic waves. The agreement between results obtained with the cross-correlation of the noise records and from the ballistic waves is remarkable, especially at periods below 60 s. We applied the same analysis to two other pairs of stations located in US (Figures 2c–2d). For the path between stations CMB and TUC that crosses tectonically active provinces of the Western US we measure relatively slow group velocities while for the path between CCM and HRV lying within the stable platform we obtain high group velocities similar to predictions from the ballistic waves. We also computed the cross-correlation at two stations located in the North Western Pacific (Figures 2e–2f). Here, we also make a comparison with group velocities measured from a local earthquake occurred in vicinity of one of

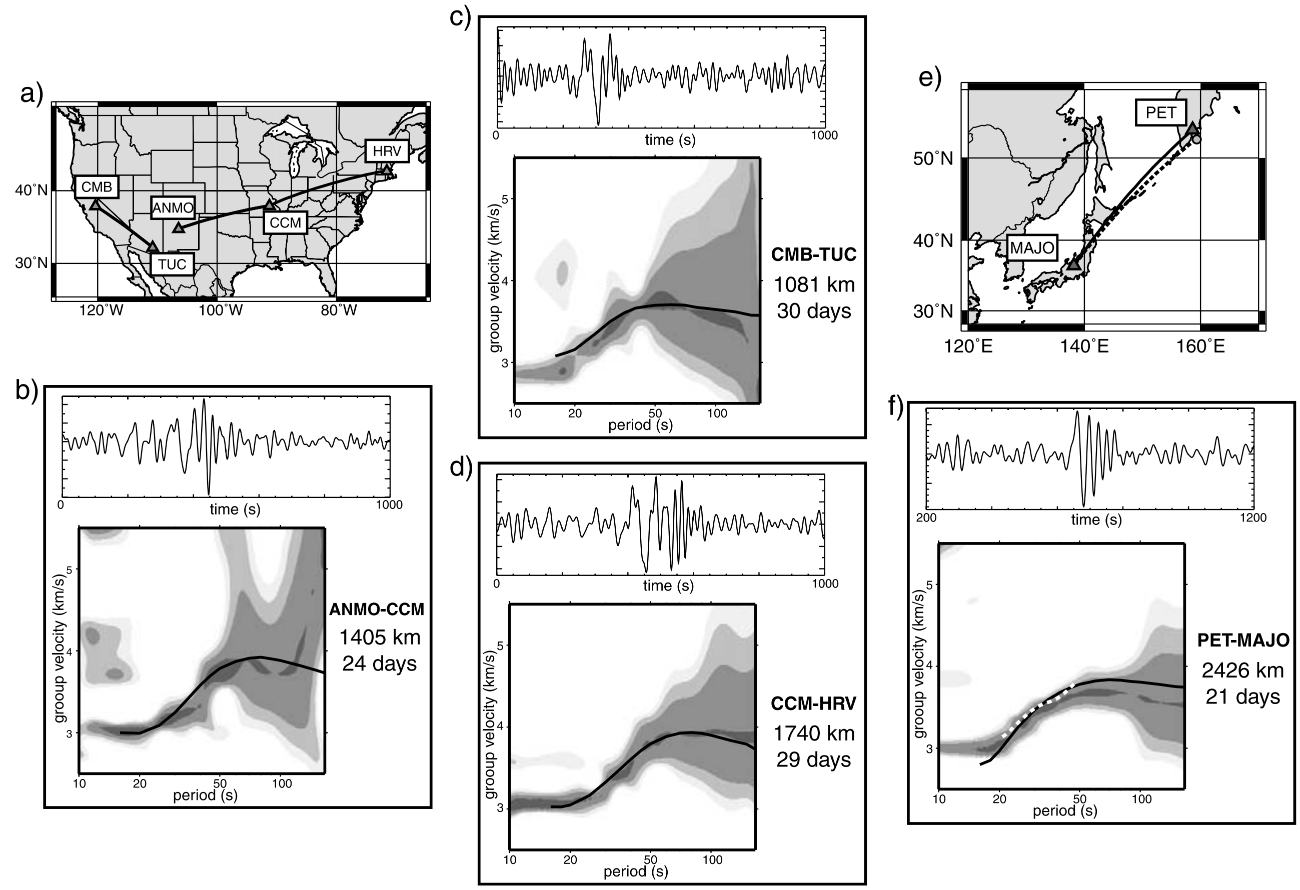

Figure 2. Analysis of broadband (0.008–0.07 Hz) cross-correlations computed for four pairs of stations from the continuous 1SPS vertical component channel recorded between January 10 and February 8, 2002. (a) Maps showing locations of stations in US. (b)–(d) results for three pairs of stations in US. (e) Map showing location of stations in North Western Pacific. (f) Results for stations PET and MAJO. For each pair of stations, the upper frame show the cross-correlation that has been high-passe filtered at 0.05 Hz to emphasize the long-period part of the emerging signal. The lower frame shows the comparison of a period group-velocity diagram computed from this cross-correlation with a dispersion curve (solid black line) predicted for the corresponding inter-station path from global Rayleigh-wave group velocity tomographic maps of [*Ritzwoller et al.*, 2002] computed from the ballistic surface waves. For each pair of stations, we indicate the inter-station distance and the total duration of the noise records available. For the path PET-MAJO, we also compare the period- group velocity diagram computed from the cross-correlation with the group-velocity dispersion curve (dotted white line) measured from an earthquake located near the coast of Kamchatka (1995/04/01, 05:50:18, 52.26N, 159.04E) and recorded at MAJO.

stations (PET) and recorded by the other station (MAJO). All three measurements agree very well at periods smaller than 50 s. Computation of cross-correlations at more regional scale is presented in Figure 3 that shows results obtained in Southern California using records of TERRAscope stations. It can be seen that, at distances of a few hundreds of kilometers, short period Rayleigh waves emerge very clearly from the noise. At longer distances, the short-period signal can be obscured by strong attenuation. Making dispersion measurements at short period is very important to obtain better estimations of the crustal structure and to improve the vertical resolution of the seismic tomographic models [e.g., *Shapiro and Ritzwoller*, 2002].

4. Discussion

[8] Our examples clearly demonstrate that fundamental-mode Rayleigh wave emerges from the correlations of the ambient seismic noise. This suggests a possibility to measure broadband Rayleigh wave dispersion curves between any desired pair of seismic stations. Development of methods that will explore this possibility is a topic for future research that, as we hope, can be stimulated by this paper. Estimating the accuracy of the measurements made from the seismic noise will be critical for the success of those methods.

[9] Surface-wave measurements made from the seismic noise can be specially advantageous with dense arrays of seismometers when they can be made for many paths and directions that cannot be sampled with the ballistic waves. Moreover the measurements made from the noise has significant advantages relative to measurements obtained with the direct waves. First, those measurements can be done for any direction of propagation. Second, they do not depend on the source location and phase (equation (3)). Third, the sensitivity zone of those measurements is local-

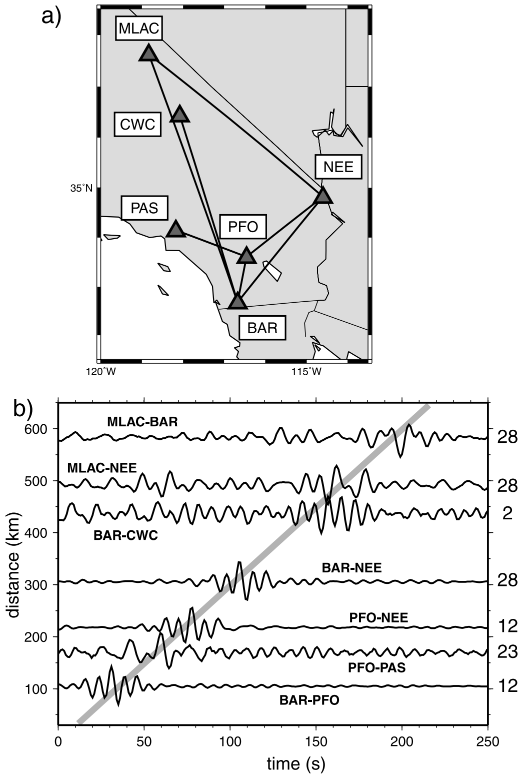

Figure 3. (a) Map showing six TERRAscope stations located in California. (b) Stacked cross-correlations of vertical-component short-period (5–30 s) computed from continuous records taken between 03/11/1996 and 04/09/1996. Gray line indicates times corresponding to velocity of 3 km/s. Total durations in days of the noise records available for each pair of stations is indicated on the right side of the plot.

ized in a narrow region connecting two stations. Fourth, the measurements can be extended to short periods if relatively closely located stations are available. As a consequence, the new measurement techniques can help to improve both the horizontal and the vertical resolution of the seismic tomographic models.

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