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THE SEISMOLOGICAL SOCIETY OF AMERICA
400 Evelyn Ave., Suite 201
Albany, CA 94706-1375
(510) 525-5474; FAX (510) 525-7204
www.seismosoc.org

Short Note

Validating Accuracy of Rayleigh-Wave Dispersion Extracted from Ambient Seismic Noise Via Comparison with Data from a Ground-Truth Earthquake

by Feng Bao, Sidao Ni, Jun Xie, Xiangfang Zeng, Zhenhong Li, and Zhiwei Li

Abstract In order to validate the accuracy of estimated Green's functions (EGFs), which are widely used in ambient seismic noise tomography, a broadband seismograph was installed in the epicentral area of an **M** 5 earthquake, with ground-truth location from Interferometric Synthetic Aperture Radar observations. EGFs between this station and permanent stations are compared with surface waves excited by the earthquake. The group velocity dispersion measured from EGFs at large interstation distances (~ 1000 km or longer) are consistent with measurements from the earthquake, and the EGFs from symmetric noise correlation functions (NCFs) are usually more accurate. At shorter interstation distances (300–1000 km), the match between noise and earthquake dispersion is good for most stations, although we observed mismatch for a few stations. The mismatch is probably caused by low signal-to-noise ratio of NCFs or nondiffusive noise wavefield at short distances.

Online Material: Figure showing mismatch of group velocity dispersion between earthquake and noise data, and figure of phase velocity dispersion between earthquake data and noise correlation functions at station ENH.

Introduction

Ambient noise tomography (ANT) is a recent breakthrough in seismic imaging technologies. Based on theoretical derivations and acoustic experiments, the full Green's function is demonstrated to be retrievable from cross correlation of ambient noise recorded on a pair of receivers (stations) (Weaver and Lobkis, 2001; Shapiro and Campillo, 2004; Snieder, 2004). Based on group or phase velocity dispersion measured in noise correlation functions (NCFs), ANT studies have been conducted to image crustal and upper-mantle velocity structure on both regional and continental scales (Ritzwoller *et al.*, 2011). Compared to earthquake surface-wave tomography, which features longer period and suffers from inaccurate source parameters (location, depth, origin time, etc.), the resolution of ANT is substantially improved and tectonic features are revealed in unprecedented detail.

The validity of ANT requires evenly distributed noise source, diffusiveness, or equipartition of energy in the noise wavefield (Snieder, 2004; Zhan and Ni, 2010). Ambient noise in the 2–30 s frequency band, also called microseism, is mostly generated by ocean waves (Bromirski, 2009). However, microseismic source distribution is inhomogeneous, as manifested by spatially varying ocean wave height (Young,

1999; Kedar *et al.*, 2008), and the inhomogeneity of noise sources is usually used to explain the asymmetry of NCF and the precursors to interstation surface waves (Stehly *et al.*, 2006; Zhan *et al.*, 2010). Furthermore, recent studies about the 26 s microseism and the Kyushu Island signal demonstrate another case of extremely spatially inhomogeneous microseismic source, the persistent and localized noise sources (Shapiro *et al.*, 2006; Zeng and Ni, 2010; Xia *et al.*, 2013). Numerical simulation with smooth distribution of noise sources suggests that noise source inhomogeneity does not substantially affect the accuracy of the estimated Green's function (EGF) when signal-to-noise ratio (SNR) of the interstation surface wave is high (Yang and Ritzwoller, 2008). However, the real distribution of noise sources on the Earth is not well resolved, and independent validation of EGF is needed.

Shapiro and Campillo (2004) demonstrated that EGFs from NCFs provide similar Rayleigh-wave group dispersion to that predicted by 3D earthquake surface tomography between 0.008 and 0.07 Hz. EGFs are also very close to surface waves in the 0.05–0.1 Hz band from earthquakes in California (Shapiro and Campillo, 2004). However, directly comparing

Figure 1. (a) Seismograph stations (solid triangles, Global Seismic Network stations; open triangles, China Earthquake Network Center stations) used in this study. The lines indicate station pairs used from computing the noise correlation function. In the inset, the portable seismograph station (SNI) is displayed with the ground displacement of the Suining earthquake as obtained from InSAR. (b) Recorded section of noise correlation functions between SNI and permanent stations.

EGFs and earthquake records requires accurate source parameters, such as origin time, locations, focal depth, and focal mechanisms (Barmin *et al.*, 2011; Xie *et al.*, 2011; Zhan *et al.*, 2011). The horizontal location error of moderate earthquakes may be up to a dozen kilometers, which may introduce significant arrival shift (~ 5 s for 15 km mislocation for short-period surface wave) in surface-wave dispersion measurement, especially for short epicentral distances ($\sim 5\%$ for 300 km). To minimize the effect due to mislocation in comparing noise and earthquake data, it is necessary to use seismic records from shallow ground-truth events. We therefore designed a field experiment by installing a broadband seismic instrument in the epicentral area of a shallow earthquake ($\sim M$ 5) to compare the dispersion between noise EGF and earthquake surface wave and then assess accuracy of EGFs.

Data

On 30 January 2010, an M_s 4.8 earthquake occurred near Suining, a city in the center of Sichuan basin of China (Fig. 1a), and the strong short-period R_g wave and short interval between teleseismic pP and P waves argue for a very shallow depth of 2 km or less (Luo *et al.*, 2011). One coseismic interferogram was formed from a pair of Advanced Land Observation Satellite (ALOS)/PALSAR images (20100119–20100306) using the Jet Propulsion Laboratory/Caltech ROI_PAC software (version 3.1 beta; Rosen *et al.*, 2004). The topographic phase contribution was removed using a version of the Shuttle Radar Topography Mission 3 arcsec (~ 90 m) spacing digital elevation model that has the voids filled with other data sources (Jarvis *et al.*, 2008), and the interferograms

were unwrapped using the SNAPHU algorithm (Chen and Zebker, 2000) to obtain line-of-sight displacements of ~ 10 cm (Fig. 1b). Modeling the event as an elastic dislocation (e.g., Li *et al.*, 2011) suggests that this moderate event had a very shallow centroid depth of 0.44 km with a centroid location of 30.284° N, 105.696° E. From the coseismic deformation observed with Interferometric Synthetic Aperture Radar (InSAR), the rupture length is shorter than 2 km (Fig. 1b), which is consistent with an earthquake weaker than M 5. Such a very shallow moderate event is very valuable for validating noise EGFs due to their compact source dimension.

Because the location of Suining earthquake is accurately determined, a broadband temporary seismograph (SNI station, short for SuiNing) consisting of a Güralp CMG-3ESPDC with flat response in the 0.02–60 s band, was installed in its epicentral area in March 2011. Because the centroid location is near a river and roads that cause substantial noises, the station was installed about 1.5 km from the centroid location to alleviate contamination from cultural noises. Fifteen months of continuous high-quality data were acquired. Continuous vertical-component seismic data for the same time span were requested from Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC), including seismic stations from the Global Seismic Network (GSN) (IC/II/IU network; Fig. 1a). We also collected continuous waveform data from the China Earthquake Network Center (CENC) to complement the sparse GSN stations.

Similar to the standard noise cross-correlation processing methods (Bensen *et al.*, 2007), linear trend and instrument responses were removed as the first step of data preprocessing.

Table 1
Source Parameters of the Suining Earthquake

Origin Time (yyyy/mm/dd hh:mm:ss.s)	Latitude 1 (°E)	Longitude 1 (°N)	Focal Depth 1 (km)	Magnitude 1 (M_s)	Latitude 2 (°N)	Longitude 2 (°E)	Focal Depth 2 (km)	Magnitude 2 (M_w)
2010/01/30 21:36:57.4	30.28	105.71	5	4.8	30.28398	105.6956	0.6	4.68

Latitude 1, longitude 1, and depth 1 are from the earthquake catalog (see [Data and Resources](#)). Latitude 2, longitude 2, and depth 2 are inverted from Interferometric Synthetic Aperture Radar (InSAR) ground deformation data.

In order to investigate whether time-domain normalization influences surface-wave dispersion, the noise data was processed in two ways. That is, we generated two sets of NCFs, one with the time domain running-average method as proposed by [Bensen *et al.* \(2007\)](#) and the other without the time-domain normalization. Because recent research demonstrates that convergence toward a stable NCF is faster for waveform segments shorter than one day ([Seats *et al.*, 2012](#)), the 15-month continuous waveform data are partitioned into two-hour segments. After the preprocessing, the two-hour-long segments of the 15 permanent stations were cross correlated with those of the SNI temporary station to obtain NCFs, which are then stacked to get final NCFs for the entire 15 months. Some authors proposed that symmetric NCFs (summation of the positive time-lag section and the negative time-lag section of NCFs) may suppress directivity of noise fields ([Yang and Ritzwoller, 2008](#)). In order to investigate whether symmetric NCFs outperform one-sided NCFs, we get final NCFs by stacking the one-sided NCFs and symmetric NCFs.

The group velocity dispersion measurement is based on the multiple-filter technique ([Dziewonski *et al.*, 1969](#)), and the CPS software package is used ([Herrmann, 1973](#)). Usually the interstation distance has to be three time longer than the surface wavelength ([Bensen *et al.*, 2007](#)), and all the station pairs used in this study meet the requirement for surface-wave periods up to 30 s. Group velocity dispersion for the earthquake is measured on the vertical ground velocity seismograms with instrument response removed. The location of the earthquake is taken from the estimated centroid location from InSAR observations, and the hypocentral origin time of the earthquake is obtained from *P* arrivals (Table 1). The origin-time error is expected to be less than 0.5 s due to the 1D-like structure of the Sichuan basin. Theoretically, the group dispersion measurement should be based on centroid origin time (the hypocentral origin plus half of the source duration); however, for the Suining earthquake with magnitude less than *M* 5, the time difference is expected to be minor (less than 0.5 s).

Results

Various studies demonstrated that directivity of the noise field is mostly from coastal toward inland regions ([Stehly *et al.*, 2006](#)), and the directivity is thought to have some bias on surface-wave dispersion. Therefore, we first compare dispersion for stations near the sea (TATO and HKPS) and then for stations far inland (AAK and KURK, in central

Asia). NCF waveforms and earthquake waveforms are displayed on the left side of Figure 2, and comparisons of the group velocity dispersion measured from NCFs and the earthquake waveforms are displayed on the right. In this figure, all four stations are at least 1000 km away from the earthquake (and from station SNI), and we refer to this distance range (1000 km+) as “far distances”. Because studies that image the crust and upper mantle with the ambient seismic noise at regional or continental scale mostly use the period band between 5 and 40 s, we only present a comparison of surface-wave dispersion for wave periods between 10 and 30 s. EGFs, including symmetrical (time-reversed) and one-sided (using the stronger energy branch) cross correlations, were used to compare dispersion measured from earthquake waveforms. From the left side of Figure 2, the Rayleigh waves in the NCFs waveforms overall match earthquake waveforms after being band-pass filtered between 10 and 30 s, and the Rayleigh-wave group velocity dispersion curves from NCFs and the earthquake data also agree well with each other. Moreover, dispersion from symmetric NCFs matches dispersion from the earthquake data better than that measured on one-sided NCFs (the strong energy branch is chosen). The difference between dispersion from symmetric NCFs and earthquake data is mostly less than 0.03 km/s (or less than 1%), which falls in the error bounds of dispersion measurement in many ANT studies.

Then we investigate the difference of Rayleigh-wave group velocity dispersion between NCFs and earthquakes for distances less than 1000 km. There are three permanent stations in GSN within 1000 km from the Suining earthquake: ENH (367 km), XAN (516 km), and KMI (641 km). Waveforms of NCFs and earthquake records are displayed on the left side of Figure 3, and a comparison of dispersion from NCFs and earthquakes is displayed on the right. Although the waveforms of NCFs and the earthquake have similar shape, dispersion measurements show noticeable differences. For the closest station (ENH), the difference in group velocity is larger than 0.2 km/s (or about 6%) at the period from 15 to 25 s. Unexpectedly, the dispersion curve extracted from one-sided NCFs is more similar to the one from the earthquake data than from symmetric NCFs. In contrast, for the XAN station, which lies to the northeast of SNI, the dispersion curves from symmetric NCFs and earthquake data match better, although still with difference up to 0.1 km/s (or 3%). For station XAN, dispersion from the one-sided NCF is different from that from the earthquake data up to 0.2 km/s, suggesting

Figure 2. (Left) Noise correlation functions and surface-wave records at far stations (> 1000 km) for stations AAK, KURK, TATO, and HKPS (from top to bottom). (Right) Rayleigh-wave group velocity dispersion curves measured from earthquake data (solid line), symmetric (dashed lines), and one-sided (starred lines) NCFs for the same four stations.

that symmetric NCFs produce more accurate dispersion than do one-sided NCFs for this station. For both ENH and XAN, a mismatch of 3% between dispersion from NCFs and earthquake data is observed. For KMI, which is southwest of SNI and further away, the match between dispersion measured

from NCFs and earthquake data is much better than those for XAN and ENH.

As there are only three GSN stations within 1000 km, the observed mismatch is not statistically meaningful. We then processed data at 10 more stations from CENC,

Figure 3. (Left) Noise correlation functions and surface-wave records at near stations (< 1000 km) for stations XAN, ENH, and KMI (from top to bottom); interstation distances are 516, 367, and 641 km, respectively. (Right) Rayleigh-wave group velocity dispersion curves measured from earthquake data (solid line), symmetric (dashed lines), and one-sided (starred lines) NCFs for the same three stations.

covering distances of 300–1000 km (Fig. 4), for a total of 13 stations within 1000 km. We observe that 9 of the 13 stations show a good match between earthquake and noise dispersions (the group velocity difference is within 0.1 km/s). Only four stations show differences up to 0.2 km/s (ENH, XAN, GSWXT, and SCSPA).

Seas *et al.* (2012) demonstrated that the accuracy of NCFs also depends on the time span of ambient seismic noise data; therefore, we compare dispersion from the earthquake and from NCFs for different time spans of noise data. In Figure 5, dispersion curves from NCFs computed with 3-month data, 6-month data, and all the 15-month data are compared with the dispersion from earthquake data for stations AAK (Fig. 1a) and ENH (Fig. 1b). Indeed, there are some differences between dispersion from NCFs of different

time spans, but the three dispersion curves are overall very similar. For AAK (epicentral distance of 3090 km), dispersion curves from NCFs of all three time spans match the earthquake data measurements well. In contrast, for ENH, the mismatch between the dispersion curves from NCFs and the earthquake data persists for all three time spans. Therefore, differences in group velocity dispersion between NCF and earthquake data should be a stable feature for ENH and XAN and is not due to a limited time span of noise data. Yang and Ritzwoller (2008) also propose that noisy data longer than one year usually led to stable NCFs.

Discussions

The difference between dispersion from NCFs and earthquake data might be due also to differences in source

Figure 4. Comparison of group velocity dispersion between earthquake data (solid) and NCFs (dashed line, the stronger branch of one-sided NCFs; starred line, symmetric NCFs). (a) NCFs are retrieved from normalized noise with the time-domain running-average method (Bensen *et al.*, 2007). (b) NCFs are retrieved from noise data without the time-domain running-average method.

Figure 5. (a) Group velocity dispersion curves from earthquake data (black) and from the NCF between stations SNI and AAK for different time spans (red, symmetric NCF from the whole 15 months of noise data; green, symmetric NCFs from six months of noise data; blue, symmetric NCF from three months of noise data). (b) Same as (a), but for the station pair SNI-ENH.

mechanisms and focal depth. NCFs between vertical components approximate the Green's function with vertical single forces loading on one of the stations, whereas the earthquake source is usually double couple and buried at depth. To explore the effects due to differences in source mechanism and focal depth, we compute synthetic seismograms at station ENH for a source located at the portable station SNI with a single vertical force acting on the free surface and for a

double-couple source with focal depths from 1 to 11 km. The focal mechanism for the Suining earthquake (strike/dip/rake $356^\circ/69^\circ/95^\circ$) is taken from Luo *et al.* (2011). Velocity model by Xie *et al.* (2012) is used in computing the synthetic seismograms. We next measured the difference between Rayleigh-wave group velocity from the synthetic seismograms for the single force and double-couple source. From Figure 6, the difference in dispersion due to single force and double

Figure 6. Rayleigh-wave group velocity difference (ΔU) between synthetic seismograms of single vertical-force source and double-couple source. Color denotes focal depth of double-couple source.

couple is small (<0.03 km/s) for shallow depth (<5 km) for the 10–30 s period. Therefore, for the Suining earthquake, which is very shallow (<2 km; [Luo et al., 2011](#)), the difference in dispersion from NCF and earthquake data at ENH is not due to differences in source mechanism and focal depth. This is also consistent with the study by [Levshin et al. \(1999\)](#), who proposed that source effects are not pronounced at short periods when measuring Rayleigh-group velocities.

The group velocity dispersion mismatch at station ENH could be partly due to the low SNR of surface waves on the NCF (Fig. 3). In order to test the possible link between SNR and dispersion mismatch, we compute the SNR and dispersion mismatch for all 17 stations. The SNR of the NCF is defined as the ratio between the peak amplitude of an interstation Rayleigh wave and the standard deviation of the NCF data for the time window before the arrival of the Rayleigh wave. The dispersion mismatch is defined as the standard deviation of the difference between earthquake and noise Rayleigh-wave group dispersion for the period between 10 and 30 s. As expected, the dispersion mismatch generally decreases with larger SNR, but with some scattering (Fig. S1, available in the electronic supplement to this article). Therefore, SNR could be one of the factors in causing the mismatch. We also test another line of evidence for the role of SNR in causing the group dispersion match by comparing phase velocity dispersion at ENH, because phase velocity dispersion measurement is usually more stable in the low-SNR situation. Because phase velocity dispersion measurement depends on earthquake source parameters, we calibrate the earthquake source param-

eter effects using a similar approach to group velocity dispersion calibration. The match in phase velocity is much better than that for group velocity (Fig. S2), supporting the proposition that high-SNR NCFs are necessary for accurate ambient-noise group velocity dispersion. However, there is a small systematic difference of about 0.1 km/s for the whole frequency band (10–30 s). Because source terms (focal mechanism and depth) have been taken into account, one of the factors for the phase velocity difference could be inaccurate origin time. But origin time cannot fully account for the mismatch, because inaccurate origin time would bias group velocity measurement in the same way as phase velocity measurement and group velocity mismatch for most stations is less than 0.1 km/s (Fig. S1). The systematic difference in phase velocity mismatch between earthquake and noise data at ENH suggests that NCF may serve as a very good approximation of Green's function, instead of an exact solution to it.

Though group velocity dispersion from NCFs is consistent with earthquake data, there are some stations showing observable mismatch at short distances (300–500 km). The distance effect on the discrepancy between dispersion from NCFs and earthquake data might be due to two effects: the dependence of Fresnel's zone upon interstation distance or the spatial distribution of the ambient seismic noise field. [Yao and van der Hilst \(2009\)](#) demonstrated that accuracy of NCFs is mostly sensitive to the first Fresnel's zone, and the Fresnel's zone is broader for shorter distances. Therefore, NCFs at shorter distances are more sensitive to inhomogeneity in the noise wavefield. Alternatively, the seismic noise field could be less diffusive for small regions (a few hundred kilometers or less) than at longer distances (1000 km or longer). As the seismic noise field is hypothesized to be partly caused by random scattering in the crust ([Shapiro and Campillo, 2004](#)), a length scale of a few hundred kilometers might not be enough for scattered wave to be completely diffusive, assuming a mean free path of 100 km ([Wu, 1985](#)). To decipher which factor is responsible for the distance effect on surface-wave dispersion mismatch, NCFs between two dense arrays may be helpful for assessing diffusivity of the noise wavefield and for quantifying Fresnel's zone effects.

The match between dispersion from NCFs and earthquake data reaffirms that NCFs provide valuable tools for tomographic studies. But the mismatch in dispersion measurements between noise and earthquake data at some short distances demands more systematic studies to validate the accuracy of NCFs as an accurate proxy of Green's functions.

Conclusions

A broadband digital seismograph was installed in the epicentral region of the 2010 Suining M_s 4.8 earthquake, which occurred in the Sichuan basin of China. With coseismic deformation well observed with InSAR, the ground-truth location of the event is accurately resolved. Cross correlations of vertical-component seismic noises were computed with 15 months of data, and the Rayleigh-wave group velocity

dispersion curves from the 10 to 30 s period were measured using the multiple-filter analysis technique. Dispersion curves from NCFs match those from earthquake data for most stations. The match is particularly good for large interstation distances (1000 km+), but there are noticeable differences for smaller distances (<~500 km) at some stations.

The overall match between dispersion curves from the earthquake data and the NCFs reaffirms that ANT is reliable. However, our study only involves comparison between dispersion from earthquake data and noise data for one ground-truth location event. Over the long term, more similar studies installing seismic stations in the epicentral region of ground-truth location events are necessary in many regions worldwide to systematically investigate the accuracy of NCF as a proxy of Green's functions. Very shallow moderate earthquakes (M 5 or less) are ideal for this purpose because their ground-truth locations can be accurately resolved with InSAR, and their rupture length is small (usually less than 3 km). Quite a few such events have been identified in stable cratonic regions such as Australia (Dawson *et al.*, 2008); these events would provide valuable opportunities for testing the accuracy of ANT.

Data and Resources

Vertical-component continuous seismic waveform data were requested from the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC) and China Earthquake Network Center (CENC). Continuous seismic waveform data at the portable seismic station SNI were collected by the authors and will be distributed to IRIS three years after the experiment ends. The pair of Advanced Land Observation Satellite (ALOS)/PALSAR images (20100119–20100306) was requested from Earth Observation Research Center (EORC)/Japan Aerospace Exploration Agency (JAXA) and processed using the Jet Propulsion Laboratory/Caltech ROI_PAC software (version 3.1 beta). Earthquake origin time and location are taken from http://data.earthquake.cn/datashare/datashare_weekphase_single.jsp?id=CB.201001310536.0001.C.001 (last accessed May 2014).

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- State Key Laboratory of Geodesy and Earth's Dynamics
Institute of Geodesy and Geophysics
Chinese Academy of Sciences
Wuhan 430077, China
sdni@whigg.ac.cn
(F.B., S.N., Z.L.)
- Mengcheng National Geophysical Observatory
University of Science and Technology of China
Hefei 230026, China
(J.X.)
- Key Laboratory of Computational Geodynamics
Chinese Academy of Sciences
University of Chinese Academy of Sciences
Beijing 100049, China
(X.Z.)
- COMET, School of Geographical and Earth Sciences
University of Glasgow
Glasgow, United Kingdom
(Z.L.)

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