Application of teleseismic long-period surface waves from ambient noise in regional surface wave tomography: a case study in western USA

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SUMMARY
Since the emerging of ambient noise tomography (ANT) in 2005, it has become a routine method to image the structures of crust and uppermost mantle because of its exclusive capability to extract short-period surface waves. Most of previous ANT studies focus on surface waves at periods shorter than 40/50 s. There are only a few studies of long-period surface wave tomography from ambient noise (longer than 50 s) in global scale. No tomography studies have been performed using teleseismic long-period surface waves from ambient noise in a regional scale, probably due to the two reasons that (1) energy of long-period ambient noise is weaker and it is harder to retrieve good signal-to-noise ratio long-period surface waves from portable stations with several years of ambient noise data and (2) long-period dispersion measurements from ambient noise may have larger uncertainties than those at shorter periods (<40/50 s).

In this study, I investigate the feasibility of using teleseismic long-period surface waves from ambient noise in regional surface wave tomography and also evaluate the accuracy of long-period dispersion measurements at periods up to 150 s. About 300 USArray/Transportable Array (TA) stations located in the Colorado Plateau and surrounding areas and 400 teleseismic stations relative to the TA stations are selected. Clear, strong, and coherent long-period teleseismic surface waves at periods much longer than 50 s are observed in the teleseismic cross-correlations between the TA stations and the teleseismic stations. Using long-period dispersion curves from ambient noise, I generate phase velocity maps at 50–150 s periods and then compare them with phase velocity maps from teleseismic earthquake data. The results show that phase velocity maps from ambient noise data and earthquake data are similar at the 50–150 s period range, verifying the validity of using long-period surface wave from ambient noise in regional surface wave tomography.

Key words: Interferometry; Surface waves and free oscillations; Seismic tomography.

1 INTRODUCTION
Traditional surface wave tomography uses earthquake surface waves to image the structures of crust and upper mantle. However, because most large earthquakes occur at plate boundaries, earthquake-based surface tomography suffers from uneven distributions of earthquakes. Especially in regional teleseismic surface wave tomography, uneven distributions of earthquakes result in unfilled azimuthal gaps in the ray coverage, which could result in smeared velocity anomalies in tomography and make it difficult to recover azimuthal anisotropy. In addition, due to strong attenuation and scattering of short-period teleseismic surface waves caused by the heterogeneous crust, it is notoriously difficult to obtain a high-resolution crustal model from earthquake surface waves. In the last decade, the advent of ambient noise tomography (ANT) has revolutionized seismic tomography because it can overcome the above limitations of earthquake surface wave tomography (Sabra et al. 2005; Shapiro et al. 2005). This technique uses diffuse background ground motion, which is conventionally called ‘ambient noise’ and mostly comes from the interaction of ocean waves with the crust (e.g. Traer et al. 2012; Traer & Gerstoft 2014), to extract surface wave empirical Green’s functions between a pair of stations by cross-correlating continuous time series of ambient noise. Within a regional seismic array, all interstation surface wave dispersion measurements can be measured and tomography can be performed to image the underlying lithospheric structures. ANT apparently has advantages over earthquake-based tomography because surface wave dispersion curves between station pairs can be measured without requiring the occurrences of earthquakes and each station can be imagined as a ‘virtual’ earthquake in addition to being a receiver.
To date, ANT has become a routine method to map the crustal and uppermost mantle structures (e.g. Moschetti et al. 2007; Bensen et al. 2009; Ekström et al. 2009, in USA; Yao et al. 2006, 2010; Zheng et al. 2011; Zhou et al. 2012, in Asia). Both Rayleigh and Love surface wave dispersion maps are commonly obtained with spatial extents ranging from regional to continental scales. Most of the existing ANT studies have focused on surface waves at periods shorter than 40–50 s because ambient noise at this period range is strong and accurate interstation dispersion curves can be easily measured. Two natural questions one may ask are (1) whether longer-period surface wave (>50 s) can also be easily extracted from ambient noise and (2) whether long-period dispersion curves from ambient noise are accurate enough for tomography to constrain upper-mantle structures.

Shapiro & Campillo (2004) have first shown that surface wave dispersion curves up to 125 s period can be retrieved from cross-correlations of ambient noise with interstation distances longer than 2000 km. However, there are only a few tomographic studies using teleseismic long-period surface waves (>50 s) in global scale (e.g. Nishida et al. 2009; Shen & Zhang 2012) and continental scales (e.g. Bensen et al. 2009). No ANT studies have been performed using teleseismic long-period surface waves from ambient noise, like 100 s period, at a regional scale with an aperture of several hundred kilometres. In global ANT studies, more than 10 yr of ambient noise data (e.g. Nishida et al. 2009) are cross-correlated to generate sufficiently high signal-to-noise ratio (SNR) long-period surface waves. It is not a problem if seismic stations used are permanent stations. However, for regional tomography, most portable arrays are usually deployed only for several years, which calls into question whether teleseismic long-period surface waves can be extracted from mere several years of ambient noise data.

In this study, I investigate the possibility of extracting teleseismic long-period surface waves from ambient noise recorded at portable seismic arrays by taking the USArrray/Transportable Array (TA) in western USA as a case study. About 300 TA stations located in the Colorado Plateau and surrounding areas and 400 permanent stations distributed globally are selected. By performing teleseismic cross-correlation of ambient noise between the TA stations and the ‘global’ stations, I observe clear, strong, and coherent long-period Rayleigh waves at periods longer than 50 s between stations with thousands of kilometres of interstation distances. To further investigate the accuracy of long-period surface wave dispersion measurements from ambient noise and demonstrate the feasibility of using them in regional surface wave tomography, I perform regional teleseismic ANT and compare resulting tomographic dispersion maps based on ambient noise with those based on earthquake data.

2 DATA AND CROSS-CORRELATIONS

In this study, the region of the Colorado Plateau and surrounding areas is selected as a case study. The Colorado Plateau is a large and stable tectonic unit with an elevation of ~1800–2000 m. Contrast to the strongly deformed regions surrounding the Colorado plateau, the plateau’s internal lithosphere is almost undeformed. In order to understand the stability and the origin of the high elevation, a number of seismic tomography studies have been carried out to image the lithosphere structure. Strong lateral velocity variations have been found with higher seismic velocities in the interior of the plateau surrounded by lower seismic velocities in the peripheries except in the northern boundary (e.g. Schmandt & Humphreys 2010; Levander et al. 2011; Liu et al. 2011). Such a region serves as a good testing site for investigating whether the ambient noise-derived long-period surface waves are able to image the strong heterogeneities of lithosphere.

About 300 TA stations located in the Colorado Plateau and surrounding areas (Fig. 1a) and about 400 permanent stations from Global Seismographic Network (GSN) and International Federation of Digital Seismograph Networks (FDSN) distributed around the globe (Fig. 1b) are selected. Teleseismic surface waves are extracted from teleseismic cross-correlation of ambient noise between
Figure 2. Examples of teleseismic cross-correlations between a teleseismic station IC.MDJ located in northeast China and the selected TA stations. (a) The great-circle paths between station IC.MDJ and the TA stations are plotted as grey lines. The cross-correlations between IC.MDJ and the TA stations are filtered at three period bands: 50–100 s (b), 100–200 s (c), 200–300 s (d).

The procedures of data processing of teleseismic cross-correlation are similar to the conventional procedures described in Bensen et al. (2007) except the stacking part. First, vertical component seismograms are filtered at a broad period band of 10–300 s after the mean and trend are removed. Because different types of seismic sensors are used among the TA stations and the ‘remote’ stations, instrument responses are removed from seismograms. The filtered and instrument response removed seismograms are then whitened in frequency domain and normalized using running average in time domain to normalize amplitude of ambient noise and meanwhile suppress the amplitudes of earthquake signals. The procedures of whitening and normalization used in this study are different from the frequency–time normalization method developed by Shen & Zhang (2012) to normalize seismograms in order to extract long-period surface waves from ambient noise.

Cross-correlations of daily segments are then performed for each possible station pair of a ‘base’ station and a ‘remote’ station. The daily cross-correlations are stacked to form monthly cross-correlations. Different from the conventional method linearly stacking the monthly cross-correlations to form the final cross-correlations, in this study, a stacking method based on S-transform (Stockwell et al. 1996; Schimmel et al. 2011) is adopted to stack monthly cross-correlations to generate the final cross-correlations. The stacking method has been proved to be effective to improve SNR of cross-correlations (Schimmel et al. 2011; Ren et al. 2013) compared to a linearly stacking method.

The finally stacked cross-correlations are folded to form the so-called symmetric components by further stacking the negative and positive time lags of each cross-correlation. At last, a method of frequency-time analysis (FTAN; Dziewonski et al. 1969; Levshin et al. 1972; Levshin & Ritzwoller 2001; Bensen et al. 2007) is applied to the symmetric components of cross-correlations to obtain phase velocity measurements at 50–250 s periods. The period dependent SNR of each cross-correlation is calculated by taking the ratio between the maximum amplitude within a surface wave window defined by a group velocity window of 3–5 km s\(^{-1}\) and the rms of trailing time-series following the surface wave time window. In the subsequent surface wave tomography, only those phase velocity measurements with SNR larger than 8 are retained for tomography. Examples of teleseismic cross-correlations between a ‘remote’ station IC.MDJ located in northeast China, and the ‘base’ TA stations located in the Colorado Plateau are plotted in Fig. 2. The distances between the station IC.MDJ and the TA stations range from 7500 to 8500 km. Clear and strong long-period Rayleigh waves emerge in
the cross-correlations with a nearly linear move-out consistent with the propagation of surface waves. Another example is for teleseismic cross-correlations between a ‘remote’ station II.SUR located in South Africa and the TA stations plotted in Fig. 3. The distances between them vary from \( \sim 14500 \) to \( \sim 16000 \) km, close to the half circumference of the earth. Clear and coherent long-period surface waves from the teleseismic cross-correlations still appear. One thing worth mentioning and emphasizing here is that the time duration of the continuous ambient noise data used in these teleseismic cross-correlations is about 2 yr, the typical deployment duration of TA stations.

Stacking over increasingly longer time series generally increase the SNR of resulting long-period surface waves. One example of increasing of SNR as a function of months of stacking between station IC.MDJ and station TA.R20A is plotted in Fig. 4 along with the cross-correlations stacked at different lengths of time-series.

One advantage of surface waves from ambient noise over earthquake surface waves is that the source term is approximately known (Snieder 2004; Lin et al. 2008) given the effective distribution of ambient noise is nearly homogenous when cross-correlation is performed over a long period of time, such as 2 yr, and time and frequency domain normalization are adopted to normalize the amplitudes of noise sources (Bensen et al. 2007). Dispersion curves from cross-correlations can be measured without the need to invert for earthquake source term. One example of surface wave dispersion curve between the ‘remote’ station IC.MDJ and a ‘base’ station TA.R20A (located in western Colorado) filtered at 50–250 s are plotted in Fig. 5(b) with the corresponding cross-correlation waveforms filtered at various period ranges plotted in Fig. 5(a). Phase velocity is calculated by measuring instantaneous phase at each period and unwrapping the phase using reference phase velocities between a station pair calculated from a Global Dispersion Model GDM52 (Ekström 2011). The measured dispersion curve (black line in Fig. 5b) is very close to the reference phase velocity curve (red dashed line in Fig. 5b). To visualize the quality of long-period surface waves, the 2-D FTAN diagram of normalized signal power as a function of time and frequency are also plotted in the background in Fig. 5(b) along with the group velocity curve (blue line) measured from the maximum amplitudes along the frequency axis. Clear and focused signals of surface waves are apparently exhibited in the 2-D FTAN diagram.

Systematic comparison between the measured dispersion curves from teleseismic cross-correlations and predicted dispersion curves from the Global Dispersion Model GDM52 provides a means to evaluate the accuracy of the dispersion curves from ambient noise.
cross-correlations with the ‘base’ stations (Fig. 6a). In the regional and quantifying their differences.

and will be performed in a future study. In this study, I mainly intend to focus on the verification of the accuracy of long-period dispersion measurements from ambient noise by comparing the tomographic dispersion maps from ambient noise with those from earthquakes and quantifying their differences.

Out of the total ∼400 selected ‘remote’ stations, about 50 per cent yield high SNR long-period surface waves from the teleseismic cross-correlations with the ‘base’ stations (Fig. 6a). In the regional surface wave tomography discussed in the following section, these ‘remote’ stations are treated as ‘virtual’ teleseismic events.

3 REGIONAL TELESEISMIC SURFACE WAVE TOMOGRAPHY

Traditionally, long-period surface waves (>50 s) are usually obtained from teleseismic events to image upper-mantle structures. However, due to scattering or multipathing caused by lateral heterogeneities along long propagating distances between earthquakes and a seismic array, teleseismic incoming waves into a regional seismic array could be distorted, causing incoming azimuths deviating away from the great-circle azimuth and leading to complex wavefields. To deal with this problem, Forsyth & Li (2005) has developed a method called two-plane-wave tomography (TPWT) by modelling an incoming teleseismic wavefield using the sum of two plane waves, each with initially unknown amplitude, initial phase and propagation direction. The sensitivities of surface waves to phase velocity heterogeneities for each plane wave are represented by 2-D sensitivity kernels (Yang & Forsyth 2006a) based on Born approximation (Zhou et al. 2004).

Because surface waves used in this method are from teleseismic events with epicentral distances typically more than 3000 km, much larger than the aperture of a study region (typical having a scale of several hundred kilometres), the interference of two plane waves is used to model an incoming wavefield. Data used in the tomography are relative phases and amplitudes of surface waves among a seismic array. Thus, the exact source mechanisms and locations of earthquakes have insignificant effects on tomographic results and can be neglected. This is an advantage over some surface wave tomography methods requiring accurate information of earthquake sources. However, the TPWT method requires both amplitude and phase data of surface waves in order to resolve incoming wavefields and phase velocity variations across a study region (e.g. Li et al. 2003; Yang & Forsyth 2006b; Yang & Ritzwoller 2008). For teleseismic surface waves extracted from ambient noise, accurate amplitudes cannot be measured from cross-correlations because amplitudes in cross-correlations are affected by azimuthal variations of strength of noise sources, the duration of cross-correlations, the normalization method applied in data processing (Lin et al. 2011), and so on. Thus, not both amplitude and phase measurements are available to model an incoming wavefield with two plane waves.

With the sole measurements of phase, as an alternative means, the incoming phase front of a teleseismic event rather than the incoming wavefield is modelled using a single plane wave with the unknown propagation direction and initial phase. Based on experiences in TPWT, one major wave of the modelled two plane waves for most teleseismic events dominates the wave amplitude with the secondary one merely having a small amplitude of about 10–20 per cent of the primary one (Forsyth & Li 2005; Yang & Forsyth 2006b). Modelling phase fronts using one simple plane wave rather than modelling the wavefield using two plane waves is sufficient enough to represent phase information of a teleseismic event. To verify this conclusion, the differences of phase velocities generated by TPWT and one-plane-wave tomography are compared. For this comparison, about 700 teleseismic events are selected from a total number of ∼1000 earthquakes occurring during 2007–2010 with $M_s > 5.5$ and epicentral distances >3000 km. The distribution of
selected teleseismic events is exhibited in Fig. 6(b). Instantaneous phases, amplitudes and SNRs of Rayleigh waves at various periods are calculated after instrument responses, means and trends of seismograms are removed. Both one-plane-wave and TPWT are applied to the selected earthquake surface waves. One example of the resulting phase velocity maps at 60 s period using one-plane-wave modelling plotted in Fig. 7 compared with the phase velocity map using two-plane-wave modelling as well as the map of differences. Phase velocity maps at 60 s period based on these two approaches are similar with an offset of the mean at 0.5 m s$^{-1}$ and a standard deviation of differences at 16 m s$^{-1}$, only $\sim$0.4 per cent relative to the regional average phase velocity of 3.86 km s$^{-1}$. The differences at other periods are similar to those at 60 s period.

4 RESULTS OF SURFACE WAVE TOMOGRAPHY

As shown in Figs 2 and 3, long-period surface waves (>50 s) are extracted from teleseismic cross-correlations of continuous ambient noise. For a dense regional array, a ‘remote’ station with several thousand kilometres away is treated as ‘virtual’ teleseismic earthquake. Similar to a teleseismic event, the incoming phase front from the ‘remote’ station is modelled as one-plane wave with unknown propagating direction and initial phase. One-plane-wave tomography is applied to long-period surface wave phase data obtained from cross-correlations between the ‘base’ TA stations and the ‘remote’ stations with interstation distances longer than 3000 km. The study area of this work is large with an aperture over 1000 km, which exceeds the limitation of one-plane-wave assumption in a Cartesian and spherical coordinates. In addition, surface wave phase fronts propagating across such a large area could have lateral variations which cannot be modelled by one single plane wave. Thus, the study region is divided into four subregions, within each of which the incoming wave front is modelled as one-plane wave. Total four plane waves are employed to represent the lateral variations of phase fronts from each ‘remote’ station. Dividing the study region into more subregions may more accurately model the incoming phase front. However, based on previous studies (Yang & Ritzwoller 2008; Yang et al. 2011), for teleseismic surface waves with epicentral distances longer than 3000 km, incoming wavefields propagating across a region with an aperture around 500–700 km can be modelled by two plane waves well. Further division of subregions into smaller regions does not result in significant and systematic changes of final phase velocity maps in tomography.

In regional surface wave tomography, we are interested in velocity anomalies in order of 100 or several hundreds of kilometres. The wavelength of a surface wave increases with period; for example, at 200 s period, the wavelength of a Rayleigh wave is $\sim$900 km, close to the aperture of the whole area of this study. Therefore, it is difficult to image lateral variations at a scale of a few hundreds of kilometres at periods as long as 200 s. Thus, in this study, regional surface wave tomography is only performed at 50–150 s periods even though teleseismic surface waves from ambient noise at periods longer than 150 s are still observed.

Resulting tomographic phase velocity maps at 50, 70, 100 and 140 s periods are plotted in Fig. 8 (left-hand column). At these periods, phase velocities are most sensitive to the shear velocities of the upper mantle. Low velocities are observed near the western, eastern and southern fringes of the Colorado Plateau. High velocities are observed in the central and north Colorado Plateau. These high velocities appear connected with the high velocities in the Wyoming craton. High velocities are also observed in central United States to the east of the Colorado Plateau. Stronger velocity contrasts are seen at intermediate periods of 50–70 s than at longer periods (>100 s) across the east boundary of the plateau. The phase velocity maps are similar to other surface wave tomography studies (e.g. Liu et al. 2011; Shen et al. 2013; Foster et al. 2014).

Here, instead of focusing on the interpretation of the phase velocity maps, I intend to evaluate the similarity of the phase velocity maps generated using ambient noise data and earthquake data. Thus, earthquake-based phase velocity maps are also generated using teleseismic surface waves from earthquakes shown in Fig. 6(b). The exactly same one-plane-wave tomography applied to teleseismic surface waves from ambient noise is applied to these earthquake surface waves.

Both sets of phase velocity maps from ambient noise data and earthquake data respectively are plotted together side by side for comparison in Fig. 8. Features of phase velocity anomalies are similar between the earthquake-derived and noise-derived dispersion maps, especially in the interiors of the study region where path coverage is dense for both data sets. Slightly larger differences at the peripheries of the study regions are observed where uncertainties of phase velocity maps also become larger because the path coverage is not as good as that in the interior area. To quantify the differences, the histogram of the phase velocity differences are presented in the right-hand column of Fig. 8 and the mean and standard deviations are calculated. Differences of phase velocities nearly follow a Gaussian distribution. The mean of differences is less than 10 m s$^{-1}$ and the standard deviation is around 30 m s$^{-1}$. Differences at 50–150 s periods are plotted in Fig. 8 at intermediate periods of 25–40 s as shown by Shen et al. (2013) using eikonal tomography for both ambient noise data and earthquake data. This may be mainly due to the fact that a larger number of data are used in the tomography of Shen et al. (2013).

5 DISCUSSION

By examining the distribution of ‘good’ ‘remote’ stations which generate high SNR teleseismic surface waves from cross-correlations with the ‘base’ TA stations (Figs 1b and 6a),
Figure 8. Resulting tomographic phase velocity maps at 50, 70, 100 and 140 s periods based on ambient noise data (left-hand column) and teleseismic earthquake data (middle column). The ambient noise- and earthquake-based phase velocity maps are plotted as perturbations relative to the same reference phase velocities of individual periods, 3.81, 3.87, 3.97 and 4.18 km s$^{-1}$ at 50, 70, 100 and 140 s periods, respectively. The histograms of differences of phase velocity maps are plotted in the right-hand column with their means and standard deviations shown at the top left of each panel.
it is noted that there is lower percentage of ‘good’ stations located in oceanic islands than those located in continents. The main reason for this is probably that local noise levels at island stations are stronger than continental stations, resulting from local interaction of oceanic waves with the island as also demonstrated by Lin et al. (2006). The local noise obscures the propagation of coherent noise signals from one station to another. It is also noted that a large number of ‘remote’ stations with their corresponding full paths passing across the Pacific Ocean, such as those stations in Australia and Antarctic, do not generate high SNR surface waves. As is well known in cross-correlations, only those noise sources propagating from either end of a station pair constructively contribute to the generation of interstation surface waves, while noise sources in the middle part between a station pair obscure the propagation of the coherent signals from the two ends (Snieder 2004; Snieder et al. 2007). As various studies show that long-period ambient noise are especially strong in the Pacific Ocean (e.g. Rhie & Romanowicz 2004, 2006; Traer et al. 2012), the energetic Pacific-originated noise sources in the middle of a station pair could destructively contribute to the coherent interstation surface waves and result in the low SNR surface waves. Another observed feature is that most of long-period cross-correlations are more symmetric, that is both positive and negative components have strong and comparable surface wave signals (Figs 2 and 3), compared with cross-correlations at shorter periods (10–40 s). The higher symmetry in cross-correlations at longer periods mostly likely results from the fact that long-period noise energy is much less attenuated by the Earth and can propagate across an entire continent from one end to the other, over much longer distances than shorter period noise, which contributes to more diffuse distribution of coherent long-period ambient noise energy between a station pair.

The high similarity between ambient noise-based and earthquake-based long-period phase velocity maps (>50 s) verifies the validity of using long-period surface waves from ambient noise in imaging lithospheric and sublithospheric upper-mantle structures. By combining teleseismic surface waves from both earthquake data and ambient noise data, better lateral and azimuthal coverage of surface wave paths can be achieved, which allows us to better image high resolution heterogeneities of upper-mantle structures and improve the ability to recover small-scale azimuthal anisotropy. Long-period surface waves from ambient noise are complementary to earthquake surface waves. Most of large earthquakes occur in oceanic plates either in subduction zones or in mid-ocean ridges and there are much fewer earthquakes occurring in the interior of continents. Fortunately, there are a large number of stations in continents, which can be used to create a large number of ‘virtual’ earthquakes by cross-correlation of ambient noise. These ‘virtual’ earthquakes provide ‘fresh’ teleseismic surface wave data which can never be obtained from earthquakes.

In the past decade, there has been rapid growth of large scale seismic arrays deployed around the globe, such as USArray in USA and CEArray in China, and meanwhile more and more permanent stations are also installed by many countries. Permanent stations provide a global network of potential ‘virtual’ earthquakes for portable arrays from which teleseismic surface waves can be obtained for regional surface wave tomography as shown in this study. All portable seismic arrays and permanent stations can also be cross-correlated with each other, promising to provide a huge number of dispersion measurements, which can be easily incorporated in global surface wave tomography to significantly improve data abundance and coverage, one of important aspects in advancing seismic tomography.

6 CONCLUSIONS

I have demonstrated that high SNR long-period surface waves can be extracted from cross-correlations of two years of ambient noise data from station pairs with teleseismic interstation distances. The teleseismic long-period surface waves can be used in regional surface wave tomography by treating ‘remote’ stations as ‘virtual’ teleseismic earthquakes. Long-period phase velocity maps based on ambient noise data are similar to those based on teleseismic earthquakes, indicating the long-period dispersion curves from ambient noise are reliable. Long-period surface waves from ambient noise are complementary to those from earthquakes and can be included in regional and global surface wave tomography, significantly increasing both lateral and azimuthal path coverage, which is essential to improving the imaging of high resolution heterogeneities and azimuthal anisotropy, especially at regions with large gaps of azimuthal distributions of earthquakes.

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