On the limitations of interstation distances in ambient noise tomography

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SUMMARY

Ambient noise tomography (ANT) has recently become a popular tomography method to study crustal structures thanks to its unique capability to extract short-period surface waves. Empirically, in order to reliably measure surface wave dispersion curves from time-domain cross-correlations, interstation distances between a pair of stations have to be longer than two/three wavelengths. This requirement imposed a strong constraint on the use of ANT at the long-period end at local- and regional-scale tomography studies. In this study, we use ambient noise data from USArray/Transportable Array recorded during 2007–2012 to investigate whether dispersion measurements from cross-correlations of ambient noise at short interstation distances are consistent with those at long distances and whether the short-path dispersion measurements can be used in tomography, especially in local- and regional-scale tomography. Our results show that: (1) surface wave phase velocity dispersion curves measured by a frequency-time analysis technique (FTAN) from time-domain cross-correlations are consistent with those measured by a spectral method tracing the zero crossings of the real part of cross-spectrum functions in frequency domain; (2) dispersion measurements from time-domain cross-correlations with short interstation distances, up to only one wavelength, are consistent with and also reliable as those with interstation distances longer than three wavelengths and (3) these short-path measurements can be included in ANT to improve path coverage and resolution.

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

1 INTRODUCTION

It has been proved that surface wave Empirical Green’s function (EGF) between two receivers can be retrieved by cross-correlating continuous ambient seismic noise recorded at the two receivers (Lobkis & Weaver 2001; Snieder 2004; Shapiro et al. 2005). Ambient noise tomography (ANT) based on retrieved EGFs has become a popular method to image crustal structures thanks to its unique capability to extract short-period surface waves (<40/50 s). Numerous studies of ANT have been performed across the globe to study seismic structures of the crust (e.g. in USA: Moschetti et al. 2007; Bensen et al. 2008; Ekström et al. 2009; Ekström 2013; in China: Yao et al. 2006, 2008; Zheng et al. 2011; Zhou et al. 2012; in Europe: Villaseñor et al. 2007; Yang et al. 2007; Li et al. 2010; Verbeke et al. 2012; in Australia: Arroucau et al. 2010; Saygin & Kennett 2010; Young et al. 2011). In ANT, both group and phase velocity dispersion curves of surface waves are measured from cross-correlation functions (CCF) of ambient noise. Most of ANT studies performed to date use a frequency-time analysis technique (FTAN; Dziewonski et al. 1969; Levshin et al. 1972; Levshin & Ritzwoller 2001; Bensen et al. 2007) to extract group and phase velocities from CCFs performed in time domain (e.g. Bensen et al. 2007).

Based on the experience of analysing a large number of data sets, Bensen et al. (2007) suggest that in order to measure group velocities reliably and accurately from CCFs, the interstation distance between a pair of station needs to be longer than three wavelengths. Bensen et al. (2007) also show that phase velocity measurements are typically more reliable and accurate than group velocity measurements because the uncertainty of phase measurement of a waveform is much smaller than that of group velocity measurement based on the peak of waveform envelope. Thus, later on, a few studies of ANT have relaxed the distance cut-off from three wavelengths to two wavelengths when measuring phase velocities from CCFs (e.g. cross-correlation functions (CCF) of ambient noise. Most of ANT studies performed to date use a frequency-time analysis technique (FTAN; Dziewonski et al. 1969; Levshin et al. 1972; Levshin & Ritzwoller 2001; Bensen et al. 2007) to extract group and phase velocities from CCFs performed in time domain (e.g. Bensen et al. 2007).

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Limitations of interstation distances in ANT (Lin et al. 2009; Porritt et al. 2011; Mordret et al. 2013). Following Bensen et al. (2007) and considering the far-field approximation in the interpretation of CCFs as EGF (e.g. Snieder 2004), most of ANT studies, however, still adopt the three-wavelength requirement to select CCFs for tomography.

This two/three-wavelength requirement imposes strong constraints on the period range where ANT can be performed for a local or regional seismic array. For example, for a seismic array with an aperture of 100 km, the longest period at which ANT can be carried out is $\sim 10$ s with the three-wavelength requirement or $\sim 15$ s with the two-wavelength requirement if the phase velocity at these period ranges is $\sim 3.0$ km s$^{-1}$. On the other hand, the requirement also forces us to discard a significant portion of CCFs with short separations, which may be able to provide good constraints on small-scale heterogeneities if they could be included in tomography.

To overcome this two/three-wavelength requirement and include short-separation paths in tomography, Ekström et al. (2009) have developed a novel technique to perform cross-correlations in frequency domain rather than in time domain, and then extract phase velocity measurements directly from the zero crossings of the real part of the correlation spectrum functions (CSF; hereafter referred to as the spectral method).

They show that phase velocity can be measured at station separations as short as one wavelength; and dispersion maps generated by using short-path CSFs are very similar to the counterparts by using long-path CSFs.

Because most of ANT studies performed to date are based on time-domain CCFs, a natural question one may ask is that whether phase velocities measured from time-domain CCFs with short paths less than two/three wavelengths are also reliable and could be incorporated in ANT. Theoretically, Tsai & Moschetti (2010) have illustrated that the frequency domain spectral method is indeed equivalent to the time domain cross-correlation method. However, there is still not much empirical work using a large dataset to investigate this question. With continuous ambient noise data available from the USAArray/Transportable Array (TA), a huge number of CCFs with different station separations can be generated, which provide a unique opportunity to address this question. In this study, by using CCFs between station pairs from about 1000 TA stations, we empirically investigate (1) whether phase velocity dispersion measurements based on FTAN and the spectral method are consistent with each other at different interstation distances, (2) whether the dispersion curves of short-separation CCFs are consistent with those of long-separation ones when both of them are measured from time-domain CCFs using FTAN and (3) if they are consistent, whether these short-separation time-domain CCFs can be included in ANT.

2 DATA

Continuous vertical-component seismic noise data recorded by $\sim 1000$ TA stations (Fig. 1) operating in 2007–2012 are collected to obtain interstation CCFs by cross-correlating ambient noise data. The data processing procedures applied here are very similar to those described in detail by Bensen et al. (2007). Raw continuous seismic data are cut into daily segments after being decimated to 1 sample per second. The mean, trend and instrument responses are removed from the daily data. The daily data are then band-pass filtered at 5–100 s. The pre-processed daily data are then normalized in time domain and whitened in frequency domain to suppress earthquake signals and instrumental irregularities prior to performing cross-correlation. Daily cross-correlations are computed between all station pairs and then stacked to produce stacked cross-correlations. To improve the signal-to-noise ratio (SNR) of surface wave signals,
the causal and acausal parts of each cross-correlation are stacked to obtain symmetric components.

Only those CCFs with SNR of surface waves larger than 10 are retained for dispersion measurement. Period-dependent SNR is defined as the peak signal in a Rayleigh wave signal window divided by the rms of the trailing noise. The Rayleigh wave signal window is defined by the time window calculated using a group velocity range of 2–4 km s\(^{-1}\). We also discard a small number of outliers that are internally inconsistent with the majority of data. The internal consistence among dispersion measurements is examined and identified during tomography as described in Section 5. The outliers with travel time misfits larger than half period of surface waves are discarded.

3 COMPARISON BETWEEN FTAN AND THE SPECTRAL METHOD

FTAN is applied to the retained CCFs to measure interstation phase velocity dispersion curves. The details of the FTAN version used here can be found in Levshin & Ritzwoller (2001) and Bensen et al. (2007). Basically, phase velocities are measured by measuring instantaneous phases of each cross-correlation at various periods and unwrapping the instantaneous phases using a global reference phase velocity model GDM52 (Ekström 2011). We trace phase velocity dispersion curves from long periods to shorter periods because cycle skipping at long periods can be identified and avoided more easily given the interstation distances are typically less than 3000 km in this study.

Using time-domain CCFs, Luo et al. (2012) developed a revised spectral method to obtain cross-spectrum functions (CSF) by simply Fourier-transforming time-domain CCFs to frequency-domain CSFs and then extract phase velocity measurements from the zero crossings of the real part of CSFs following Ekström et al. (2009). The revised spectral method of Luo et al. (2012) is different from the spectral method of Ekström et al. (2009) in that the spectral method of Ekström et al. (2009) directly calculates CSFs in frequency domain. However, Luo et al. (2012) have shown that CSFs obtained by the two different procedures of data processing give almost same phase velocity measurements. Thus, in order to investigate whether phase velocities calculated by FTAN and the spectral method are consistent with each other, we measure phase velocities using FTAN and the revised spectral method of Luo et al. (2012) both from the time-domain CCFs rather than calculating all the CSFs in frequency domain exactly following the method of Ekström et al. (2009).

Boschi et al. (2013) compared phase velocities measured by FTAN from time-domain CCFs and those by the spectral method of Ekström et al. (2009). Their results show that phase velocities measured by these two methods are consistent with each other.

In this study, we use a much larger data set to compare the measurements, and furthermore investigate whether the consistency is similar for cross-correlations with different interstation distances. Four examples of phase velocity dispersion curves are presented in Fig. 2 for CCFs between station pairs with their paths marked in Fig. 1. Clearly, phase velocity dispersion curves measured by FTAN and the spectral method are very close to each other with average difference less than 15 m s\(^{-1}\). For systematic comparison, we take about 350 000 dispersion measurements and divide them into three subclasses based on their separations \(r\) relative to surface wave wavelength \(\lambda\): (1) \(r \geq 3\lambda\), (2) \(3\lambda < r \leq 2\lambda\) and (3) \(2\lambda < r \leq \lambda\). The reason why we do not include paths with \(r < \lambda\) for comparison is that dispersion measurements from CCFs with \(r < \lambda\) have larger uncertainties compared with those with \(r > \lambda\), and the number of the returned measurements from these paths with \(r < \lambda\) is too small for statistical comparison.

One example of the histograms of differences between phase velocities measured by FTAN and those by the spectral method at 25 s period is plotted in Fig. 3. The histogram of differences for all the combined dispersion measurements at 10–50 s period range is also plotted in Fig. 4. In addition, Table 1 summarizes the differences of phase velocity by listing the means and the standard deviations of the differences at nine periods at 10–50 s period range.

The means of differences are almost close to zero for CCFs at all the periods and at all the three distance ranges, having the largest mean of differences at only \(\sim 2\) m s\(^{-1}\) for paths with \(r \leq 3\lambda\). There is no noticeable systematic variation of the mean with period and interstation distance. The standard deviations are about 10 m s\(^{-1}\) for paths with \(r \geq 3\lambda\) and increase to \(\sim 20\) m s\(^{-1}\) for paths with \(\lambda < r < 2\lambda\). The slight increase of the standard deviations with decreasing interstation distances is because that uncertainties of phase velocities measured by both FTAN and the spectral method slightly increase with decreasing distances. However, considering the phase velocities are around 3–4 km s\(^{-1}\) at the 10–50 s period range, the 20 m s\(^{-1}\) standard deviations are relatively small, only about 0.5 per cent relative to the phase velocities. We do not notice there is any systematic variation of the standard deviations with
Figure 3. Histograms of the differences between phase velocities measured by FTAN and those measured by the spectral method at 25 s period. The phase velocity measurements are divided into three interstation distance ranges as indicated at the bottom of each panel. The differences for all measurements combining the three ranges are presented in the top left-hand panel.

As demonstrated by Ekström et al. (2009), phase velocity measurements from short-separation CSFs, as short as one wavelength, based on their spectral method are robust and consistent with long-separation ones. It is, however, generally assumed that phase velocities measured from time-domain CCFs using FTAN are only reliable for those with separations longer than two/three wavelengths. However, Table 1 and Figs 3 and 4 demonstrate that the two approaches actually provide consistent phase velocity measurements from CCFs at all the three distance ranges. Based on this, we suggest that the interstation distance cut-off of two/three wavelengths imposed in selecting phase velocity dispersion curves from time-domain CCFs using FTAN may be relaxed to as short as one wavelength.

When CCFs of ambient noise contain both fundamental mode and higher mode surface waves, which are rare for continental paths but have been observed, especially in a sedimentary basin or on the seafloor at short periods (e.g. Savage et al. 2013; Takeo et al. 2014), measurements of fundamental-mode phase velocities will be affected by the presence of overtones. In these cases, time domain CCFs need to be inspected prior and different mode of surface waves needs to be separated before applying the FTAN and the spectral methods to accurately measure the fundamental-mode phase velocity measurements.

4 EVIDENCE BASED A THREE-STATION METHOD

To provide another line of evidence for the suggestion of relaxing the interstation distance cut-off and meanwhile to further investigate if dispersion measurements using FTAN from short-separation
Figure 4. Same as Fig. 3, but for phase velocity measurements combining all the data at 10–50 s period range. Note the differences of counts at each panel between Figs 3 and 4.

Table 1. Summarized differences of phase velocity calculated by FTAN and the spectral method (evaluated as FTAN’s results minus the results of the spectral method). Slashed cells mean that the number of measurements at that distance range and that period is too small for statistical comparison.

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>Mean misfit (m s$^{-1}$)</th>
<th>Standard deviation (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>$r \geq 3\lambda$</td>
</tr>
<tr>
<td>10–50</td>
<td>0.04</td>
<td>0.12</td>
</tr>
<tr>
<td>10</td>
<td>0.02</td>
<td>/</td>
</tr>
<tr>
<td>15</td>
<td>−0.14</td>
<td>−0.14</td>
</tr>
<tr>
<td>20</td>
<td>0.16</td>
<td>0.18</td>
</tr>
<tr>
<td>25</td>
<td>0.26</td>
<td>0.32</td>
</tr>
<tr>
<td>30</td>
<td>−0.10</td>
<td>−0.2</td>
</tr>
<tr>
<td>35</td>
<td>−0.00</td>
<td>0.14</td>
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<tr>
<td>40</td>
<td>−0.1</td>
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<tr>
<td>45</td>
<td>−0.13</td>
<td>−0.17</td>
</tr>
<tr>
<td>50</td>
<td>0.03</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Figure 5. Histograms of the phase velocity differences $V_{\text{dif}}$ at 10 s period among station-triples at three categories indicated at the bottom of each panel. All the phase velocity data are measured by FTAN.

Two pairs: $r \geq 3\lambda$ and one pair: $2\lambda \leq r < 3\lambda$

Figure 6. Same as Fig. 5, but for phase velocity measurements at 25 s period.

Two pairs: $r \geq 3\lambda$ and one pair: $\lambda \leq r < 2\lambda$
time-domain CCFs are consistent with those with long separations, we select a series of station-triples, which have three stations almost exactly aligning in a common great-circle path as Lin et al. (2008) and Ekström (2013) did before. Considering three stations in a station-triple named as a, b and c from one end of the great-circle path towards the other end, we have three station pairs of a–b, b–c and a–c with their corresponding separations and phase velocities named as \( D_{ab}, D_{bc} \) and \( V_{ac} \), respectively. Two strict criteria are adopted to ensure the three stations almost align in a common great-circle path: (1) the interstation distances between the three stations pairs need to satisfy \( D_{ab} + D_{bc} - D_{ac} < 0.1 \) km; and (2) the corresponding differences of azimuth angles between the three paths need to be smaller than 1°.

If dispersion measurements from CCFs with short paths and long paths are consistent with each other, for a station-triple, the phase velocity \( V_{ac} \) for a surface wave propagating from station a to c should be almost the same as the combined phase velocity \( V_{ac}' \), defined as \( V_{ac}' = (D_{ab} + D_{bc})/(D_{ab}/V_{ab} + D_{bc}/V_{bc}) \), for a surface wave propagating from a to b first and then from b to c. Thus, to evaluate the consistency, we examine the velocity difference between \( V_{ac} \) and the combined velocity \( V_{ac}' \), defined as \( V_{dif} = V_{ac}' - V_{ac} \), and also the travel time difference between \( T_{ac} \) and the combined travel time adding \( T_{ab} \) and \( T_{bc} \), defined as \( T_{dif} = (D_{ab}/V_{ab} + D_{bc}/V_{bc}) - T_{ac} \). In order to normalize time difference for different periods and paths with different distances, we also calculate the percentage of traveltime difference as \( T_{pdif} = T_{dif}/T_{ac} \times 100 \% \). We examine station-triples belonging to three categories defined based on the station-pair separation \( r \) and surface wave wavelength \( \lambda \): Category I: all the three pairs with \( r > 3\lambda \); Category II: one pair either a–b or b–c with \( 2\lambda \leq r < 3\lambda \) and the rest two with \( r > 3\lambda \); Category III: one pair either a–b or b–c with \( \lambda \leq r < 2\lambda \) and the rest two with \( r > 3\lambda \).

The histograms of \( V_{dif} \) among the station-triples belonging to each of the three categories are plotted separately in Figs 5 and 6 for 10 and 25 s period surface waves respectively. The histograms of \( V_{dif} \) for combined data including all the measurements at nine periods, explicitly indicated at Table 2, are plotted in Fig. 7. The distributions of \( V_{dif} \) are nearly following a Gaussian distribution. Thus, we calculate the means and the standard deviations of the differences, which are shown at the top right corner of each panel.

Table 2 summarizes the comparison of \( V_{dif}, T_{dif} \) and \( T_{pdif} \) among the three categories of station-triples for the combined data of the nine periods.

Table 2 shows that the average means of \( V_{dif}, T_{dif} \) and \( T_{pdif} \) are \( \sim 2 \text{ m s}^{-1}, \sim 0.2 \text{ s} \) and \( \sim 0.06 \text{ per cent} \), almost close to zero, and the average standard deviations of them are \( \sim 16 \text{ m s}^{-1}, \sim 0.9 \text{ s} \) and \( \sim 0.4 \text{ per cent} \). There are no significant variations of the means and standard deviations of \( V_{dif}, T_{dif} \) and \( T_{pdif} \) among the three categories of station-triples. We also calculate the differences for phase velocity measurements based on the revised spectral method of Luo et al. (2012), which are presented in Table 3. Similar differences of the measurements based on the revised spectral method are observed with those based on FTAN. Tables 2 and 3 and Figs 5–7 confirm that phase velocity measurements made by FTAN and the revised spectral method from short-separation time-domain CCFs, as short as one wavelength, are consistent with those from long-separation ones. These results are consistent with those of Ekström et al. (2009) and Ekström (2013).

### 5 COMPARISON OF PHASE VELOCITY MAPS

Base on the comparison of phase velocity measurements made by FTAN and the revised spectral method and the three-station method presented in the two preceding sections, we can conclude now that surface wave dispersion measurements by FTAN from time-domain CCFs are consistent with those measured by the spectral method, and dispersion measurements from short-path CCFs are as reliable and accurate as those from long-path CCFs. Because dispersion measurements from CCFs are finally used to generate phase velocity maps by ANT, we investigate whether phase velocity maps derived solely from short-path dispersion measurements are consistent with those solely based on long-path ones.

We divide dispersion measurements made by FTAN into two data sets according to their separations \( r \) relative to their surface wavelength \( \lambda \): one with \( \lambda \leq r < 3\lambda \), and the other with \( 3\lambda \leq r < 5\lambda \). We perform tomography for both data sets using a tomography method of Barmin et al. (2001). The reason why we do not include dispersion measurements with distances longer than five wavelengths is that long-path surface waves may be slightly influenced by
no-straight-ray behaviour (Ekström 2013), such as the off-great-circle propagation. We do not include measurements with interstation distances shorter than one wavelength because the number of available measurements at that short distance is very small, and the uncertainties of measurements are large as also mentioned in Section 3.

The tomography method of Barmin et al. (2001) has been applied for numerous ANT studies before (e.g. Moschetti et al. 2007; Bensen et al. 2008; Zheng et al. 2011). The details of this method are documented in Barmin et al. (2001). Here we choose an area extending from −113° E to −96° E and from 32° N to 48° N and parameterize it to a 0.5° × 0.5° grid for tomography. We use same regularization parameters in the tomography for the two data sets, which implies that any differences between the two sets of tomography results are purely resulting from the differences of data.

Fig. 8 shows the two sets of resulting phase velocity maps at 25, 35 and 50 s periods based on the long-path data set (left-hand column) and the short-path one (middle column), respectively. The histograms of corresponding differences between the two sets of phase velocity maps are also plotted in the right-hand column of Fig. 8. We do not show the comparison of phase velocity maps at periods shorter than 25 s because the number of paths with distances shorter than three wavelengths at this short-period range is too small for tomography. As shown by Fig. 8, the two data sets generate almost identical phase velocity maps with the means of velocity differences ranging from ~2 to ~7 m s⁻¹ and the standard deviations from ~13 to ~19 m s⁻¹ at different periods.

These small differences between the two sets of phase velocity maps again affirm that phase velocity dispersion measurements by FTAN from short-path time-domain CCFs are consistent with those from long-path ones, and short-path dispersion measurements with distance as short as one wavelength can be retained for ANT to increase path coverage and subsequently improve resolution.

6 DISCUSSION AND CONCLUSIONS

This study has demonstrated that surface wave phase velocity dispersion curves measured by FTAN from time-domain cross-correlations of ambient noise is consistent with those measured by the zero crossing of the real CSFs, and the dispersion measurements at short interstation distances, as short as one wavelength, are consistent with and also reliable as those at distances longer than three wavelengths. These short-path dispersion measurements can be included in ANT, which is typically discarded in previous ANT studies. Short-path dispersion measurements are extremely useful to constrain small-scale velocity anomalies in local and regional ANT (Ekström 2013).

The inclusion of short-path dispersion measurements in ANT helps to extend the range of the long-period end in ANT when the extent of a seismic array is limited. For instance, if a seismic array covers a region with an aperture of 300 km, the conventional requirement of three-wavelength inter-station distance limits the longest period of tomography to ~30 s. If we include the short-path data like one wavelength, surface wave tomography could be extended up to periods as long as 60/70 s, which provides constraints on uppermost mantle structures. Recently, there are a few studies showing that long-period surface waves at periods up to 200/300 s can be extracted from cross-correlations of ambient noise (e.g. Shen & Zhang 2012; Yang 2014). The relaxation of the two/three wavelength limitation on interstation distances to one wavelength allows long-period surface waves from ambient noise to be included in regional tomography, enabling ANT to image upper mantle structures which is mostly constrained by earthquake surface wave data before.

The inclusion of short-path dispersion measurements from ambient noise could also help to better resolve azimuthal anisotropy in tomography. It is well known there is trade-off between azimuthal
Figure 8. Phase velocity maps at 25, 35 and 50 s periods generated using long-path dispersion measurements with $3\lambda \leq r < 5\lambda$ (left-hand column) and short-path dispersion measurements with $\lambda \leq r < 3\lambda$ (middle column) as well as the corresponding histograms of the differences between the two sets of maps (right-hand column). The numbers of paths used in tomography are indicated on the top of each phase velocity map.

Figure 8. Phase velocity maps at 25, 35 and 50 s periods generated using long-path dispersion measurements with $3\lambda \leq r < 5\lambda$ (left-hand column) and short-path dispersion measurements with $\lambda \leq r < 3\lambda$ (middle column) as well as the corresponding histograms of the differences between the two sets of maps (right-hand column). The numbers of paths used in tomography are indicated on the top of each phase velocity map.

anisotropy and lateral heterogeneities in surface wave tomography. The better constraints on small-scale heterogeneities and the better lateral and azimuthal coverage obtained by including more short-separation paths are helpful to better resolve the trade-off. However, Harmon et al. (2010) have demonstrated that variations in phase velocities with azimuth resulting from inhomogeneous distribution of noise sources could yield up to 1 per cent apparent peak-to-peak azimuthal anisotropy. As we mention in the preceding section, the uncertainties of phase velocity measurements increase slightly with the decreasing interstation distances, the questions of whether and
how the inclusion of short-path dispersion measurements in ANT eventually improves the inversion of azimuthal anisotropy is still needed to be further investigated in future studies.

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