2012 SCEC Project Report
Improving High-Frequency Site Response with Ambient Noise

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Summary:
The long-term goal of this project is to achieve improved high-frequency (>0.5 Hz) site amplification response maps by utilizing ambient noise observations. However, in order to achieve this goal, a number of steps are necessary to be taken first. In particular, there are two primary reasons why station-station ambient noise correlations cannot be used without modification as direct characterization of the station-station Green's functions, from which site response can be inferred. The first issue is that the distribution of ambient noise sources affects the amplitude decay of the wavefield such that the source distribution is partly responsible for the amplitude variability observed. The second issue is that wavefield effects like focusing/defocusing of wave energy and intrinsic attenuation also cause significant amplitude variability that must be accounted for before site response can be reliably retrieved.

To address these two major problems, we have focused on three primary research topics: (1) Developing a theoretical understanding of ambient noise amplitudes, including how these amplitudes change seasonally to affect velocity measurements; (2) developing a robust method of wavefield analysis which extends the method of Helmholtz tomography to apply to the amplitudes of surface waves; and (3) testing this new version of Helmholtz tomography on earthquake data from USArray.

For (1), we have performed a theoretical analysis of how noise correlation amplitudes decay with distance under different idealized noise distributions. We found that coherency amplitudes have large biases in many situations but that raw cross correlations have much smaller biases (Tsai & Zhan, 2012). We also determined the smoothness criteria necessary for amplitudes to decay as expected, and further found that certain forms of processing (like C^3 processing) can enhance the effective source distribution if the station distribution is optimal (Tsai & Zhan, 2012). Finally, we determined theoretically how frequency variability in noise maps into observed changes in correlation measurements, including velocities (Zhan et al., 2013).

For (2), we have extended the method of Helmholtz tomography by explicitly including both site amplification and attenuation, and tracking both the real and imaginary parts of the Helmholtz equation (Lin et al., 2012a). Applying this methodology to USArray earthquake data has allowed us to construct low-frequency, low-resolution maps of site response (achieving goal (3)). We have also applied similar methodology to measuring horizontal/vertical amplitude ratios, which further constrains site response (Lin et al., 2012b). While this has so far been applied only to earthquakes, ambient noise application is expected.

Technical Report:

In this work, we primarily address the three topics reviewed in the summary. They are: (1) Developing a theoretical understanding of ambient noise amplitudes, including how these amplitudes change seasonally to affect velocity measurements; (2) developing a robust method of wavefield analysis which extends the method of Helmholtz tomography to apply to the amplitudes of surface waves; and (3) testing this new version of Helmholtz tomography on earthquake data from USArray. In the following two sections, we describe these findings.

1. Theoretical Understanding of Ambient Noise Amplitudes

We build on Tsai (2011), who provided a straightforward framework for evaluating the effect of ambient noise distributions on the retrieved amplitude decay as a function of interstation spacing. In the original work, a few simple distributions of noise were tested and it was found that coherency measurements had a strong bias dependent on the radial distribution of sources.

In our extension, we first evaluate the smoothness constraints on the noise and find that the average weighted noise amplitudes need to be equal within all Fresnel zones as the interstation distance changes (Tsai & Zhan, 2012). This implies that there may be important cases where the strong variability in noise source distribution is mapped incorrectly into differences in amplitude decay. The left panel of Fig. 1 shows an example of this, caused by the unevenness of azimuthal noise distributions.

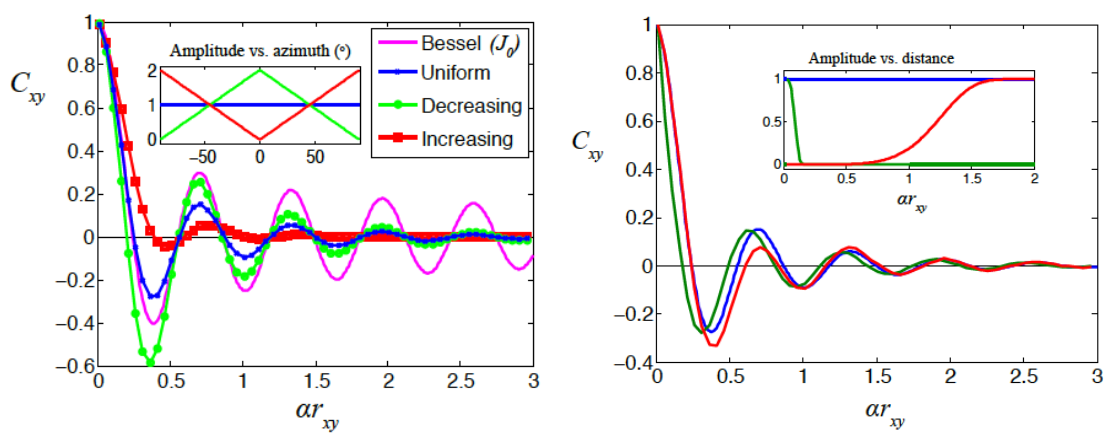

Figure 1 (from Tsai & Zhan, 2012): (Left panel) Normalized cross correlation amplitude versus normalized interstation distance. Magenta curve is the Bessel function whereas the 3 other curves are for the 3 azimuthal distributions shown in the inset. (Right panel) Same as left panel for the 3 radial distributions shown in the inset.

Second, we determine the differences in the amplitude decays for raw cross correlations, which turn out to be significantly different from those of coherency that were previously evaluated by Tsai (2011). As shown in the right panel of Fig. 1, although there is some dependence of the amplitude decay on the noise distributions, the bias is relatively small compared with the severe biases seen for coherency measurements.

Theoretical arguments also suggest that C^3 processing can help improve the effective source distribution due to the fact that the distribution of scatterers modifies the effective source distribution (Tsai & Zhan, 2012). In particular, if both the distribution of C^3 stations and the distribution of scatterers is more uniform than the primary noise source distribution, then improvement in the effective source properties is improved by using C^3.

Finally, we also examine the effect that temporal variations in ambient noise frequencies have on the retrieved waveforms. We discover that there is actually a subtle tradeoff between apparent velocities and the amplitude spectrum such that one could mistakenly infer temporal changes in velocity structure that was in fact due to changes in the amplitude spectrum of noise (Zhan et al., 2013). These spurious changes are of similar magnitudes to those reported by previous authors (Meier et al., 2010), thus drawing into question the reliability of those measurements (see Fig. 2).

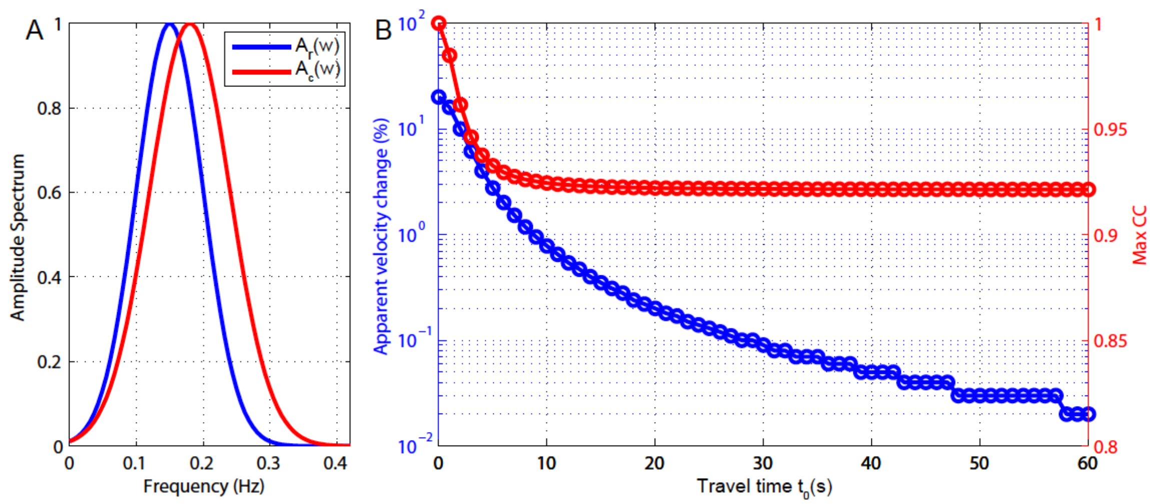

Figure 2 (from Zhan et al., 2013): (A) Two example amplitude spectra, different only by a stretched amount, i.e. $A_c(w)=A_r(w/1.2)$. (B) The blue line indicates the apparent velocity change (in percent), calculated numerically using the stretching method. The red line shows the corresponding maximum cross correlation coefficients between the reference and current waveforms. Note that the apparent velocity change is above 0.1% for travel times of less than about 30 s, and correlation coefficients are all high (above 0.9).

2. Development of Helmholtz Tomography and Applications to Earthquake Data

In previous work, Lin & Ritzwoller (2011) developed the Helmholtz tomography method, which measures phase velocities from estimates of gradients of the travel time wavefield that includes a finite-frequency focusing/defocusing correction from the inclusion of amplitude measurements. In our work, we extend the Helmholtz tomography method to explicitly account for both site amplification and attenuation, and to track both the real and imaginary parts of the Helmholtz equation (Lin et al., 2012a). Specifically, the real and imaginary parts of the Helmholtz equation (respectively) become

$$\frac{1}{c^2} = \nabla\tau \cdot \nabla\tau - \frac{\nabla^2(A/\beta)}{\omega^2(A/\beta)} \qquad (1)$$

$$-\frac{2\alpha}{c} = \frac{2\nabla(A/\beta)\cdot\nabla\tau}{A/\beta} + \nabla^2\tau \qquad (2)$$

where c=phase speed, τ=phase travel time, A=amplitude, β=site amplification, and α=attenuation coefficient (Lin et al., 2012a). These two equations show that array measurements of τ and A can be used to determine maps of c, β and α. The reason that the effects of β and α can be separated is that the β dependence is directionally dependent, whereas the α dependence is independent of direction.

To demonstrate the new method, we apply this modified Helmholtz tomography method to earthquake data from USArray. USArray station spacing is not of sufficiently high resolution to obtain robust high-frequency measurements, but we demonstrate that the method works well (see Fig. 3). As shown, we obtain reliable maps of site amplification, and the velocity models we obtain compare favorably with the observations.

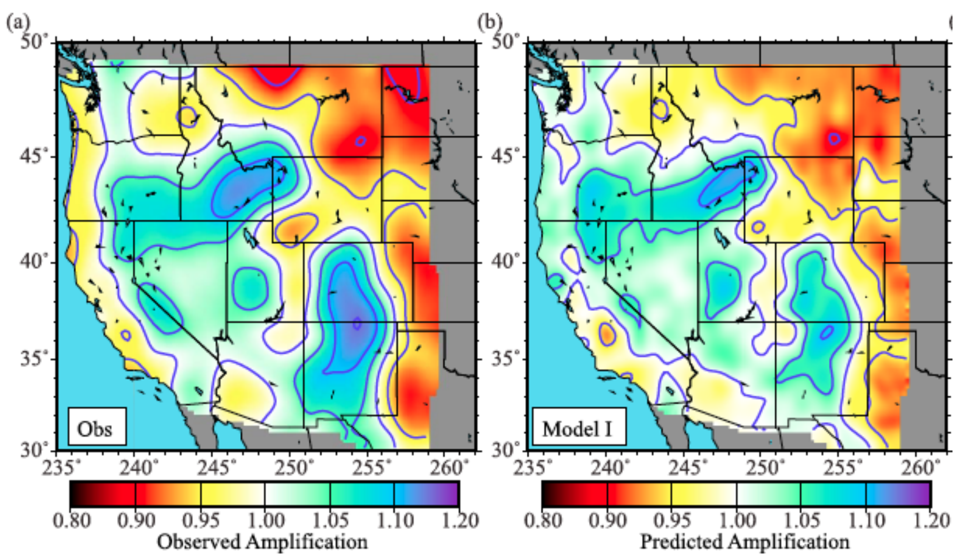

Figure 3 (from Lin et al., 2012a): (a) Observed amplification across USArray for 60-s Rayleigh waves, using the improved Helmholtz tomography method. (b) Predicted amplification for 60-s Rayleigh waves based on one of our inverted velocity models.

In other parallel work, we measure horizontal/vertical (H/V) amplitude ratios, which further constrains site response (Tanimoto & Rivera, 2008). Our inferred site amplification maps from these observations (Lin et al., 2012b) compare well with those of Fig. 3. While both the Helmholtz method and the H/V ratio method have so far been applied only to earthquakes, now that both methods have been favorably tested on earthquake data, we are confident that they can be applied well to ambient noise data, where it will be easier to go to the higher frequencies desired.

References

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Tsai, V. C., and Z. Zhan (2012), When are noise correlation amplitudes useful?, So. Calif. Earthq. Cent. Annual Meeting, Abstract.

Zhan, Z., V. C. Tsai, and R. W. Clayton (2013), Apparent velocity change caused by temporal variation of frequency content of ambient seismic noise, Geophys. J. Int., submitted.

Outreach:

VCT gave talks about geophysics to middle school student groups.
VCT volunteered to judge science fair projects at local middle schools.
VCT provided visual and textual materials for outreach and tours at the Seismological Laboratory at Caltech.

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Lin, F. C., V. C. Tsai, and M. H. Ritzwoller (2012a), The local amplification of surface waves: A new observable to constrain elastic velocities, density, and anelastic attenuation. J. Geophys. Res., 117, B06302.

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