Imaging the subsurface with ambient noise autocorrelations
Robert W. Clayton, Seismological Laboratory, California Institute of Technology

Summary
Autocorrelations created by stacks of near-offset traces from virtual source gathers are used to form an image of the deeper subsurface. The masking effects of the effective source-time function are minimized by subtracting the survey-wide average trace from each trace. The results show that the technique can be particularly useful for imaging the mid- and lower crust, where traditional seismic methods have problems. Examples are shown from a one-component 3D survey and a three-component 2D profile. The 3D example shows the crust in the transition between the continent and the Inner Borderland in the Los Angeles, CA area, and for the first time, shows an image of the lower crust. The 2D profile provides both a P-image and S-image of the basement interface in the San Bernardino Basin in S. California.

Introduction
Ambient noise correlation as an imaging tool has been in use from more than a decade, but the analysis has been predominately used for determining the near-surface shear-wave velocity with surface waves (Lin et al, 2013). Body-waves, such as refracted P-waves have also been used in a few studies to determine the shallow P-wave velocity (Nakata et al, 2015), but their general use has been impeded by dominance of surface waves in ambient noise correlations. Observation of reflected waves is even more challenging because the angular partitioning of the random noise field is dominated by horizontal moving waves. A study by Draganov (2009) shows reflections in the 9-18 Hz passband after f-k filtering to suppress surface waves. Cheraghi et al (2017) also show some reflected energy from ambient noise correlations, but that the dominant surface wave energy and limited source distribution diminish its usefulness as a mapping tool. On a large scale, Sun and Kennett (2017) used stacked autocorrelations from earthquake recorded on a permanent array in Australia to image the Moho reflection with a broad-scale horizontal resolution.

In this study, we use autocorrelations of ambient noise to image the crust from the basement to the Moho. The autocorrelations are generated from near-zero offset stacks of virtual source gathers obtained from dense seismic arrays. The technique is illustrated with two different types of arrays, both in the Los Angeles region of California, USA.

A composite shot gather is shown in Figure 1, which is a stack of all virtual sources generated from the 5200-node Long Beach survey (Lin et al, 2013). The surface waves and refracted P-waves are clear, but there are no obvious reflected phases that can be seen. The surface waves tend to mask possible reflections except in wide-angle and near zero-offset windows. Enhancement of possible reflections in the wide-angle regime requires an accurate knowledge of both the subsurface velocities and the static corrections. However, for near-zero offsets, the normal movement is minimal and static correction is constant, and hence a horizontal sum or “brute stack” can be used to enhance the signal.

Figure 1. Stack of all virtual sources for the Long Beach array. The virtual sources were generated with three weeks of correlation of the 5200-element array. The white polygon is the region for wide-angle reflections. The refracted P-waves are above this and surface wave are to the left. The autocorrelations are along the left edge (offset=0) of the section.

The near-offset stack generates an autocorrelation section. The energy source for this type of imaging is ocean microseisms and possibly the coda from distant earthquakes. This coupled with the low-end roll-off of the geophone response (in the 5-10 Hz range), restricts the effective bandwidth of the source to approximately 0.2-4.0 Hz. This low-frequency passband will generally limit the usefulness of the method to the region of the crust below the basement (particularly when compared with active source capabilities). However, the autocorrelation energy does appear to penetrate through the whole crust, and hence the method is useful for looking in a region where it has been difficult to obtained reflected energy.
Figure 2. Autocorrelation processing. Panel A shows a line autocorrelations. The trace shown in B is the average autocorrelation over the whole survey. Panel C is the results of subtracting the average from each autocorrelation trace, which now reveal subsurface structure.

The Autocorrelation Method

The first step is to construct virtual sources for an ambient noise survey

\[ C(x_i, x_j, \tau) = \int S(x_i, t)S(x_j, t + \tau)dt \]

where \( S \) are the raw seismograms, \( x \) is its location and \( C \) is the virtual seismogram. The integration is typically done over a 1 to 3 week interval. The raw data are preprocessed with a slowly varying gain control to attenuate the effect of large impulsive motions such as earthquakes (Benson et al., 2007). The virtual seismogram is often spectrally balanced (whitened), to minimize the effect of the limited bandwidth of the source.

The autocorrelations are then estimated by stacking the virtual seismograms by

\[ A(x, \tau) = \sum C(x_i, x_j, \tau) \]

where \( A(x,\tau) \) is a autocorrelation and the sum is over all traces such that the distance between and the midpoint of the correlation pair is less than \( M \) and the offset of the correlation pair is less than \( H \). For the 3D survey shown in the next section, \( M=H=0.4 \text{ km} \), resulting in a sack of approximately 50 traces. The resulting autocorrelations are shown in Figure 2, and they show a very smooth lateral variation subsurface because they are being dominated by the initial impulse (effective source-time function). The choice of \( M \) and \( H \) control the trade-off between lateral resolution and the image noise. The results do not seem to be very sensitive to the choice.

The autocorrelation for a layered medium (using an equi-time layering representation or Goulliand medium) is given by the equation (Claerbout, 1968)

\[ A(Z) = \left( I + R(Z) + R\left(\frac{1}{Z}\right)\right) \otimes S(Z) \]

where \( R(Z) \) is the reflectivity of the layered structure, \( S \) is the source time function, and \( Z \) is the time-shift variable of the Z-transform. The leading term (the I) dominates the right side of this equation and is typically 10 to 100 times larger than the reflectivity. Standard deconvolution is not very effective because the source function \( S(Z) \) is usually narrowband. Instead we attempt to minimize its affect by subtracting an estimate of \( S(Z) \) from the equation. We use as an estimate the average of all the traces in the survey, then we form an estimate of the reflectivity (in positive time) by

\[ R(Z) = A(Z) - S_{est}(Z) \]

where \( S_{est}(Z) = \sum A(Z) \).

The disadvantage of this estimation approach is that horizontal structure will also be included in the estimate of \( S \), and hence will be removed from the image. This procedure is equivalent to one step in iteration time-domain deconvolution that is commonly used in receiver function analysis (Ligorria and Ammon, 1999). This procedure is also similar to a one-component receiver function.
There are two advantages to using autocorrelations in imaging with noise correlations. The first, mentioned earlier, is that it is not
necessary to know the velocity function or static corrections to for the image. The second is that surface waves are attenuated as
the source-receiver distance goes to zero.

**Three-Component Correlations**

The use of three-component sensors allows radial and transverse directions to be used in the images. The transverse-to-transverse autocorrelation or $A_{TT}$, is sensitive to S-waves, while the radial-radial correlations ($A_{RR}$) is sensitive to S-waves. The vertical-vertical correlations ($A_{VV}$) is sensitive to the P-waves as before. Thus, with 3C instruments you can obtain P, S, and S images.

To illustrate the 3C correlations, we show and example from a 2D line of 3C node sensor deployed across the San Bernardino Basin in the Los Angeles region (Fig 4). The data from 92 nodes with an approximate spacing of 300m are shown. The results of the autocorrelation imaging are shown in Fig 5.
Conclusions

The autocorrelation method provides a means to convert ambient noise correlations into a zero-offset section. The image is enhanced by subtracting the average source from the section, but this may also remove the laterally invariant structure. The method appears to allow imaging of deeper into the crust than is possible with conventional reflection surveys.

Acknowledgements

The author thanks Signal Hill Petroleum for permission to use the Long Beach and Extended Long Beach surveys in this study. The also thank Dan Hollis for facilitating the use of these data. This work was supported by NSF/EAR-1520081 and USGS/G17AP00002.

Figure 4. Location of the 3-component node line (SB4) in San Bernardino Basin, CA. The line consists of 92 nodes on a 25-km line.

Imaging Using Autocorrelations on SB4

Figure 5. Results of 3-component autocorrelations. The top panels show the processed A_x, A_y, and A_z correlations. The bottom panels shown interpreted section with a simple constant velocity time-to-depth conversion. The right two columns are lower frequency because they are S-waves.
REFERENCES


