Imaging the Subsurface with Ambient Noise Autocorrelations

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Abstract

Autocorrelations created by stacks of near-offset traces from virtual source gathers are used to form an image of the deeper subsurface. We minimize the masking effects of the effective source time function by subtracting the survey-wide average autocorrelation from each trace. The result is a zero-offset reflection image of the subsurface generated by ambient noise correlation. The technique can be particularly useful for imaging the mid and lower crust, in which traditional seismic methods have penetration problems. We show examples from a one-component 3D survey and a three-component 2D profile. The 3D example shows the crust in the transition zone between the continent and the Inner Borderland in the Los Angeles, California, area, and for the first time, shows an image of the lower crust. The 2D profile provides both a P image and an S image of the basement interface in the San Bernardino basin in southern California.

Introduction

Ambient noise correlation is an imaging tool that has been in use for more than a decade, but the analysis has been primarily focused on determining the near-surface shear-wave velocity with surface waves (Yao et al., 2008; Lin, Li, 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. The observation of reflected waves is even more challenging because the angular partitioning of the random noise field is dominated by horizontal moving waves and not the vertical motion needed to form subcritical reflections. There have been some successful studies (Draganov et al., 2009; Nakata et al., 2011; Ruigrok and Wapenaar, 2012; Panea et al., 2014; Boullenger et al., 2015; Romero and Schimmel, 2018) in which frequency filtering is used to improve the signal level, but the issue of surface wave and additive noise contamination remains a problem. On the whole-earth scale, major interfaces have been successfully imaged using autocorrelations (Ito and Shiomi, 2012; Poli et al., 2012; Lin, Tsai, et al., 2013; Sun and Kennett, 2017).

The situation is illustrated in Figure 1, which is a stack of all virtual sources generated from the 5200-node Long Beach survey (Lin, Li, 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 subsurface velocities and 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. The near-offset stack generates an autocorrelation section.

In this study, we use autocorrelations of ambient noise to image the crust from the basement to the Moho. To overcome the noise contamination problem, 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.

Method and Examples

The first step is to construct virtual sources from the correlation

\[ C(x_i, x_j, \tau) = \int S(x_i, t)S(x_j, t + \tau)dt, \tag{1} \]

in which S are the continuous seismograms at locations \(x_i\) and \(x_j\), respectively. The integration is typically done for several days. In the first example presented in this study, the integration time is one week, and the second it is three weeks. We did not try to find the optimal correlation length, but suspect it is longer than what is necessary for surface waves because the reflection signal is much weaker. The raw data are preprocessed with a slowly varying gain control (long-window automatic gain control [AGC]) to attenuate the effect of large impulsive motions such as earthquakes (Benson et al., 2007). The virtual seismograms were spectrally balanced (whitened), to minimize the effect of
the limited bandwidth of the source (Nakata et al., 2011). For this reason, they are not strictly autocorrelations, but we keep the term for simplicity.

The autocorrelations are then estimated by stacking the virtual seismograms by

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

in which \( A(x, \tau) \) is an autocorrelation and the sum is over all traces such that the distance between point \( x \) and the midpoint of the correlation pair is less than \( M \), and the offset of the correlation pair itself is less than \( H \). \( M \) is the maximum distance between the point \( x \) and the midpoint of \( x_i \) and \( x_j \). \( H \) is the maximum distance (offset) between \( x_i \) and \( x_j \). For the 3D survey shown in the next section, \( M = H = 0.4 \text{ km} \), resulting in a stack of approximately 40 traces. The resulting autocorrelations are shown in Figure 2, and they show a very smooth lateral variation because they are being dominated by the initial impulse (the effective source time function). The choice of \( M \) and \( H \) controls the trade-off between lateral resolution and the image noise. The results do not seem to be very sensitive to the choice; however, the method does depend on having a sufficient receiver density such that the stack enhances the autocorrelation above the random noise. Examples of stacking with various choices of \( M \) and \( H \) are shown in Figure S1.

The autocorrelation for a layered medium (using an equi-time layering representation from Goupillaud, 1961, is given by the equation, Claerbout, 1968)

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

in which \( R(Z) \) 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 10–100 times larger than the reflectivity. Standard deconvolution is not very effective because the

**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 color version of this figure is available only in the electronic edition.

**Figure 2.** Autocorrelation processing. (a) Profile of autocorrelations along profile A in Figure 3. (b) The trace shown here is the average autocorrelation over the whole survey. (c) Results of subtracting the average from each autocorrelation trace, which now reveal subsurface structure.
source function $S(Z)$ is usually narrowband. Instead, we attempt to minimize its effect by subtracting from the equation, an estimate of $S(Z)$ obtained from the average of all the traces in the survey. We then form an estimate of the reflectivity (in positive time) by

$$R_{est}(Z) = R(Z)S_{est}(Z) = A(Z) - S_{est}(Z),$$  \hspace{1cm} (4)

in which $R_{est}(Z)$ is the estimated reflectivity and $S_{est}(Z) = \sum A(Z)$. This is very similar to the process used by Ruigrok and Wapenaar (2012), to enhance reflections in autocorrelations using earthquake sources.

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. Other source estimation methods, such as restricting the spatial region where the averaging is done, may reduce this restriction. For 2D deployments, removing the average may also attenuate broadside surface waves that are not cancelled in the correlation and stacking process. The method could be modified to include a spatially variable $S_{est}(Z)$, but abrupt changes in this function will likely manifest itself in the reflectivity image.

This procedure is equivalent to one step in iterative time-domain deconvolution that is commonly used in receiver-function analysis (Ligorria and Ammon, 1999), and this procedure is also similar to a vertical-component receiver function (Langston and Hammer, 2001). An example of applying this to teleseismic earthquakes recorded on the same industry array used in the first example in this article is given by Schmandt and Clayton (2013), and their results on the dip of the Moho agree with those presented here.

An example of the estimated $S_{est}(Z)$ is shown in Figure 2b. The removal of the common source function now reveals significant lateral variations in the structure. Applying AGC and looking at 10 s of two-way travel time, reveals the $P$-wave...
section of the entire crust. The resulting image (Fig. 3) shows features of the crust that had only been speculated before. There is significant apparent faulting in the basement. The lower crust is characterized by continuous horizontal lamina that is truncated against the continent-ocean boundary. This boundary (presumed to be the Moho) dips steeply (45°) inland implying that continent-ocean transition takes place within 10 km of the coast, unlike other models of this zone (ten Brink et al., 2000; Nazareth and Clayton, 2003). The tectonic implications for these images are discussed in R. Clayton (unpublished manuscript, 2020, see Data and Resources). The arrivals near the bottom of each profile appear to be multiples, although they do not have a simple timing relationship to the primaries.

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 form the image. The second is that surface waves are naturally attenuated as the source–receiver distance goes to zero, although imperfect correlation may leave some residual.

The methodology presented here can be easily extended to multicomponent data. For example, using the transverse components in equations (1) and (2) would generate the transverse autocorrelation $A_{TT}$, which, with the processing given in equation (4), leads to an SH image. Using the radial component would produce $A_{RR}$ and an SV image. The vertical component produces the $P$ image as with the vertical-only component case. The cross components such as $A_{ZR}$ and $A_{ZT}$ may also contain useful information, but this has not been explored in this study.

To illustrate the 3C correlations, we show an example from a 2D line of 3C-node sensors deployed across the San Bernardino basin in the Los Angeles region (Fig. 4) as part of the BASIN (Basin Amplification Seismic Investigation) project (Clayton et al., 2019). The results from 92 nodes with an approximate spacing of 300 m are shown. The $A_{ZZ}$, $A_{TT}$, and $A_{RR}$ autocorrelation images are shown in Figure 5. The process to create these is the same as with the single-component analysis, with $M = H = 0.4$ km. To compare the images, a simple time-to-depth scaling is done using a constant $P$-wave velocity of 2.6 km/s for the ZZ image and a constant shear-wave velocity of 1.5 km/s for the $TT$ and $RR$ images, which brings the $P$ and $S$ images into approximate alignment. A more detailed analysis could be done to refine this alignment. The results show that in all three images that there is an apparent fault in the basement (at the marked location) that is tentatively interpreted as the Red Hill fault (Liu et al., 2018). The Moho, in this example, is masked by apparent multiples from the basement.

**Discussion**

The energy source for this type of imaging is ocean microseisms and possibly the coda from distant earthquakes. Cultural noise such as vehicle traffics appears to contribute very little to useful ambient noise field, based on the observation that there is very little difference between day- and nighttime correlations. The effective source spectrum coupled with the low-end rolloff of the geophone response restricts the effective bandwidth of the method to approximately 0.2–3.0 Hz. In the examples presented here, we looked for discernable signal above 3 Hz and could not find any coherent energy. This may reflect the noisy urban environment in which the data for both examples were acquired. The 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 in some cases, and hence the method may be useful for looking at a region (i.e., the lower crust) where it has been difficult to obtain reflected energy.

The tunable parameter in this procedure is the size of the stacking disk (the $M$ and $H$ parameters) used to produce the autocorrelations. In both examples previously shown, doing no stacking resulted in very poor images. As one would expect, a

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**Figure 4.** Location of the three-component node line (SB4) in San Bernardino basin, California. The line consists of 92 nodes on a 25 km line. The average receiver spacing is 275 m. This is part of the BASIN (Basin Amplification Seismic Investigation) project (Clayton et al., 2019). The color version of this figure is available only in the electronic edition.
large stacking area reduces the lateral resolution on the images. The procedure that was used in the examples presented was to start with a large stacking disk, and reduce it until the noise started to significantly affect the image.

With the multicomponent image, aligning features in the $P$, $SH$, and $SV$ images might provide a method of estimating the $VP/VS$ ratio, and possibly look for azimuthal anisotropy.

**Conclusions**

The autocorrelation method provides a means to convert ambient noise correlations into a zero-offset section. The near zero-offset stacking used here to enhance the autocorrelations relies on a dense recording array. 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 deeper into the crust than is possible with conventional reflection surveys. It can be applied to three-component data to generate $P$ and $S$ images.

**Data and Resources**

The data associated with the Long Beach example are owned by Signal Hill Petroleum and requires permission from them to use. The data associated with the San Bernardino example will be placed in the public domain in 2021 and will be available from the Incorporated Research Institutions for Seismology Data Management Center (IRIS-DMC). The supplemental material has images with different choices of the stacking parameters. The unpublished manuscript by R. Clayton (2020), “A detailed image of the continent-borderland transition beneath Long Beach,” submitted to Geophys. Res. Lett.

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