Ambient noise cross-correlation precursor imaging using dense seismic arrays

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Abstract

When passive seismic data recorded in areas with non-uniform source distribution are employed to compute noise cross-correlations, it is possible to observe precursory energy preceding the direct arrivals. Such precursors have been theoretically explained by energy generated by scatterers present in the area (Snieder et al., 2008). These apparently unphysical events have been used to image scatterers in volcanic areas using an energy-based imaging condition (Ma et al., 2013). We present a new method to use these cross-correlation precursors to form an image of the potential scatterers present in an area. We describe a synthetic example and report an initial observation of precursory energy in noise cross-correlations obtained on seismic data recorded by a dense station array in the Seal Beach area (Jia et al., 2021).

Noise cross-correlation precursors

To simulate cross-correlation precursors caused by scatterers present in an area, we employ a simple constant velocity model in which we add a Gaussian velocity anomaly (Figure 1a). We generate data using 701 sources with a band-limited wavelet between 0.1 and 1.0 Hz recorded by two receivers (Figure 2b) and compute the cross-correlations for each source (Figure 2c). A precursor event (indicated by the red arrows in Figure 2c) due to the presence of the scatterer is visible in the resulting cross-correlations sorted by source azimuth. The summation of the cross-correlations for all azimuth cancels this energy and leads to the presence of scattered physical events (orange line in Figure 4d). However, a clear precursor is observed when only half of the azimuth is considered in the summation (blue line in the same Figure).

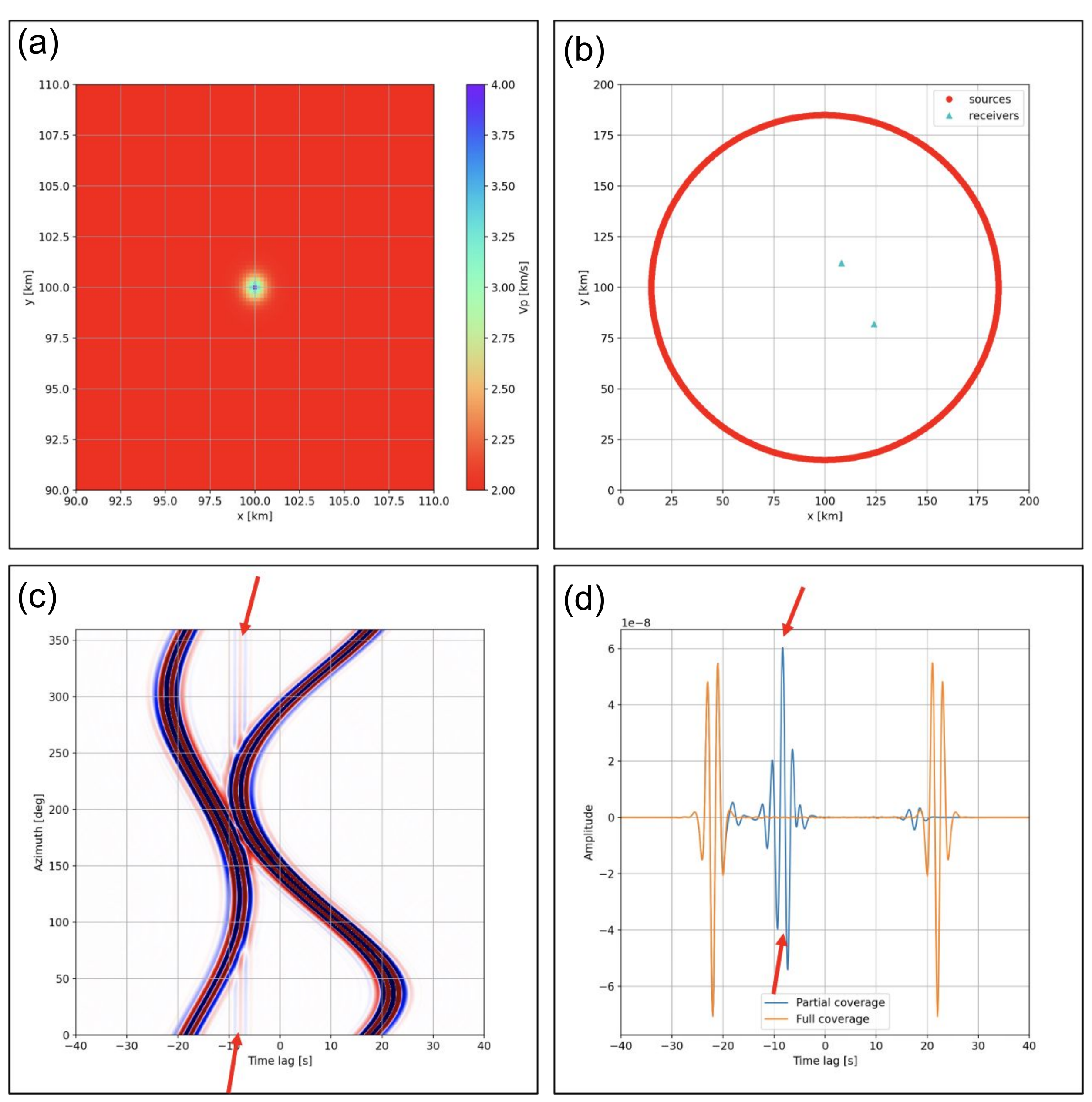

Figure 1: (a) 2D velocity model used for the synthetic precursor test. (b) Source distribution and receiver pair chosen to show an example of cross-correlation precursors. © Cross-correlations of the data recorded by the two stations as function of the source azimuth. The direct arrival has been removed. (d) Scattered-related cross-correlation arrivals. The red arrows indicate the precursor event.

Cross-correlation precursor imaging

We design a delay and sum process where the energy belonging to imaging precursors is coherently stacked to form an image of potential scatterers present in an area. The image I is formed by computing the following summation:

$$I(\boldsymbol{x},\tau) = \sum\sum CC[\boldsymbol{x}_s,\boldsymbol{x}_r,\tau-\tau_c(\boldsymbol{x},\boldsymbol{x}_s,\boldsymbol{x}_r)],$$

where **x** denotes the image point, τ is the cross-correlation lag, $\boldsymbol{x}_s$ is the virtual source position, $\boldsymbol{x}_r$ is the receiver coordinate, and τ_c is the precursor traveltime. This process effectively produces an image cube as a function of 2D spatial coordinates and a time variable. If the precursory energy is coherently summed, then this energy would focus on image positions corresponding to potential scatterer for $\tau = 0$.

Synthetic test results

We show a synthetic example of the imaging procedure on cross-correlation obtained using the model of Figure 1a. In this case, a line of stations is considered in the test and consider the image point indicated by the blue dot in Figure 2a. Figure 2b shows the source energy distribution considered in this test. While Figure 3c shows a virtual-shot cross-correlation gather where the scattered physical energy is indicated by the green arrows and the precursor by the red one, respectively. The red curve corresponds to the precursor traveltime τc. When cross-correlations formed using multiple lines of stations are used in the imaging procedure (Figures 1c), we can generate a clear image of the scattered present in the center of the domain (Figure 1d).

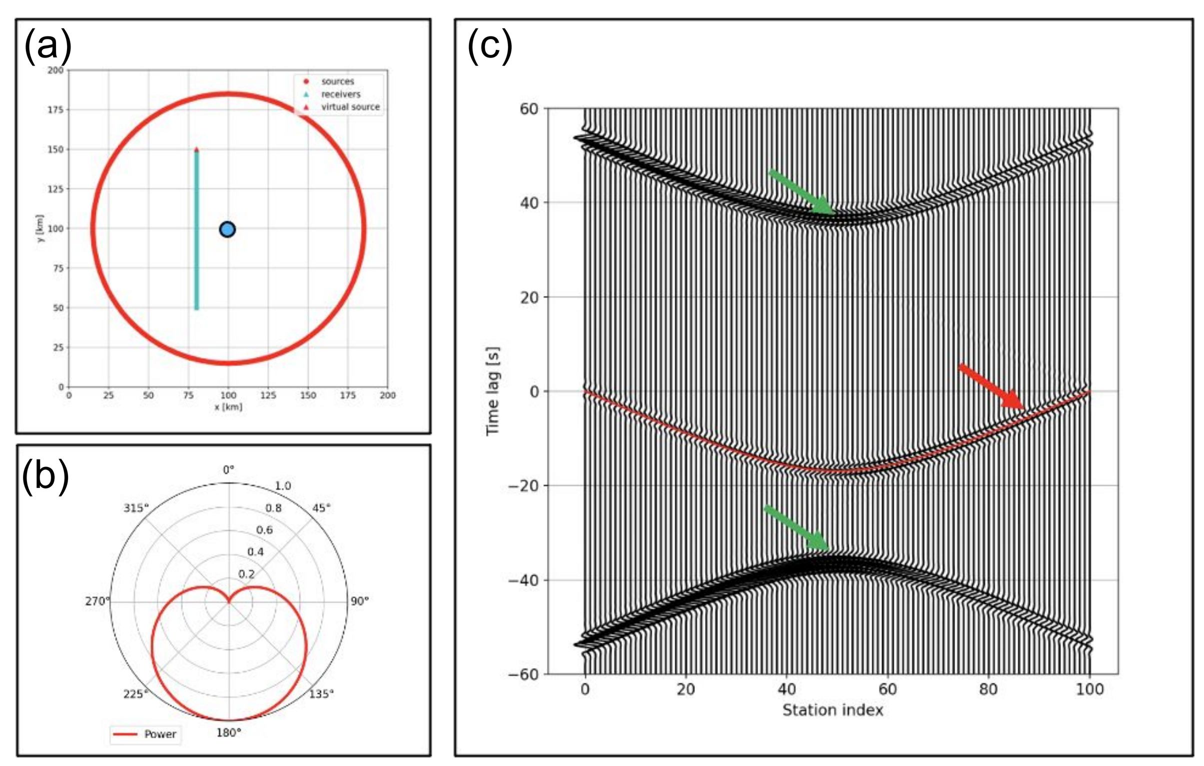

Figure 2: (a) Line of stations and imaging point chose to highlight the moveout of the precursors as function of virtual source and receivers chosen for imaging. (b) Source energy azimuthal distribution chosen in this test. (c) Scattered waves within cross-correlations obtained for the virtual source and receivers shown in (a). The red arrows indicate the precursor, while the green ones point to the physical scattered energy. In panel (c) we removed the direct arrival energy.

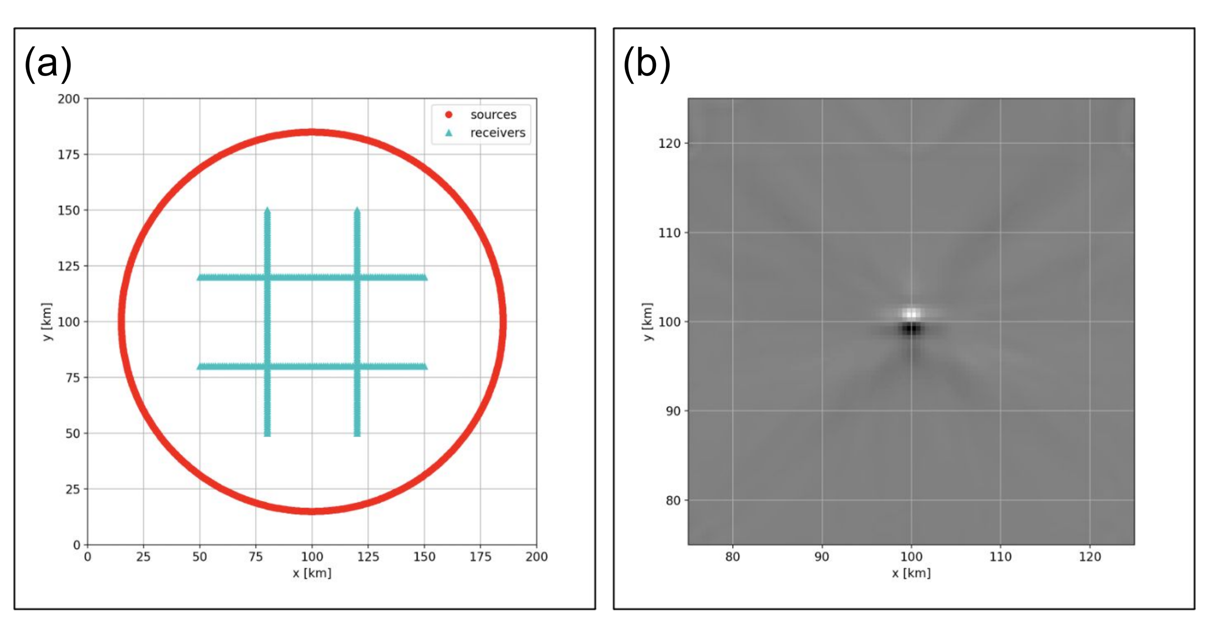

Figure 3: (a) Receivers chosen to form an image of the scatterer from cross-correlation computed using the source distribution shown in Figure 2b. (b) Zero-lag image obtained by applying the described precursor imaging procedure.

Field-data observation

A data cube is generated when a line of stations is used to compute cross-correlations for all possible stations pairs (Figure 1a). In this data volume, on the zero-lag slice, the direct arrival is located on the main diagonal of the panel, while the precursor event is orthogonal to it (Figure 4d). To find evidence of potential cross-correlation precursors in field data, we process seismic recordings from a line of stations of a dense array placed in the Seal Beach area (Figure 1c). In the latitude-binned zero-lag slice, we observe a similar pattern as in the synthetic case. In this case, the precursor energy is potentially associated with a major fault crossing the line of receivers.

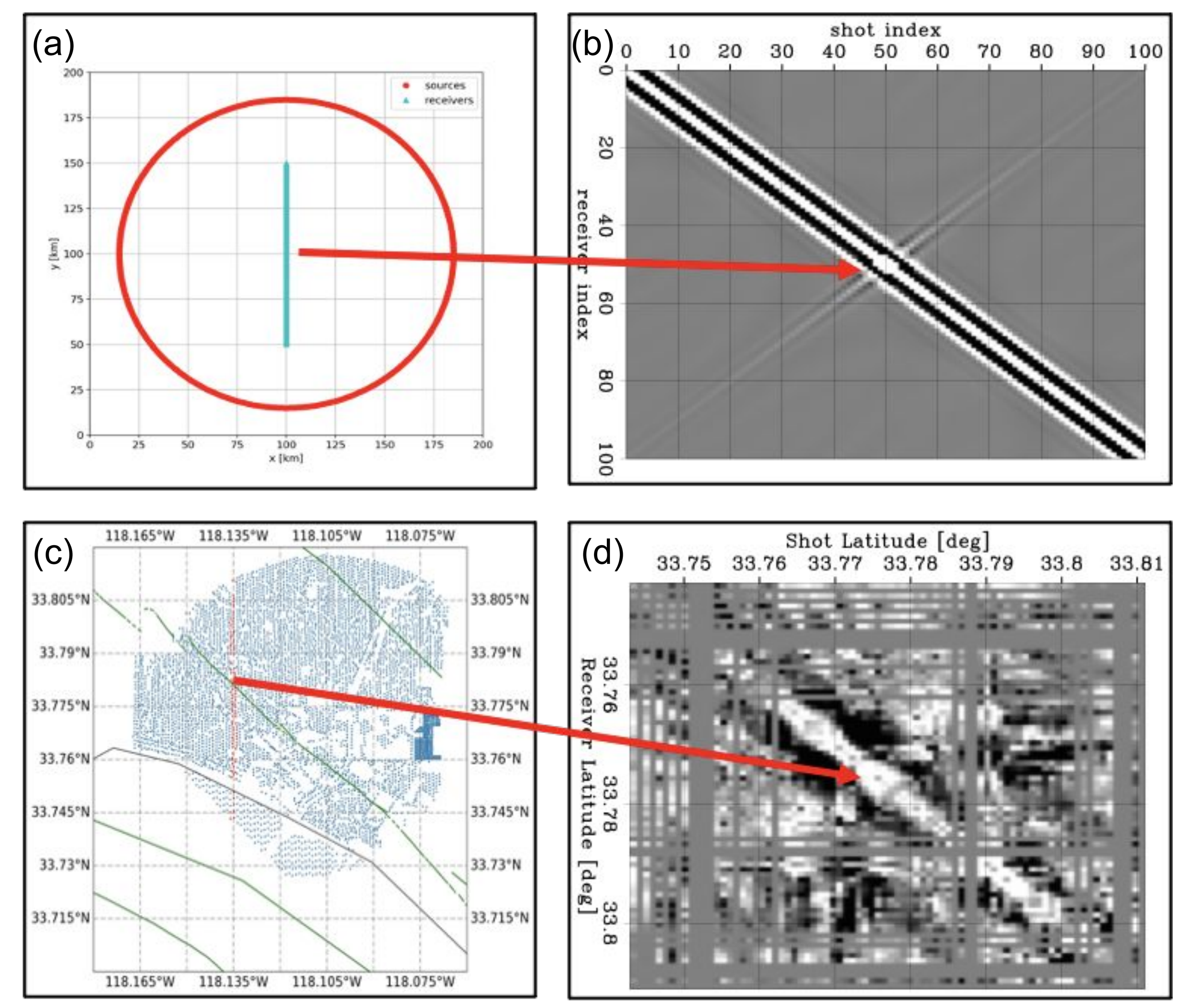

Figure 4: (a) Line of station chosen for highlighting precursor in synthetic data for multiple virtual sources and receivers. (b) Zero-lag data slice. In this panel, the direct arrival follows the main diagonal, while the precursor event is placed orthogonal to the it. (c) Map of the dense Seal Beach array station (blue dots) and of the major USGS-mapped faults (green lines). The red dots indicate the selected stations for noise cross-correlation processing. (d) Zero-lag data slice extracted from the noise cross-correlations, The direct arrival is along the diagonal, and a fairly coherence energy pack associated to the scattering potentially due to the major fault crossing the line of stations is visible. The red arrows in these panels connect the scattered locations in the corresponding figures.

Conclusions and future steps

We present a novel cross-correlation precursor image formation algorithm and show preliminary results on a synthetic example. We are currently processing data from a dense seismic array to generate an image of potential faults present in the Seal Beach area.

References

Jia, Z. and Clayton, R.W., 2021. Determination of Near Surface Shear-Wave Velocities in the Central Los Angeles Basin With Dense Arrays. Journal of Geophysical Research: Solid Earth, 126(5), p.e2020JB021369.

Ma, Y., Clayton, R.W., Tsai, V.C. and Zhan, Z., 2013. Locating a scatterer in the active volcanic area of Southern Peru from ambient noise cross-correlation. Geophysical Journal International, 192(3), pp.1332-1341.

Snieder, R., Van Wijk, K., Haney, M. and Calvert, R., 2008. Cancellation of spurious arrivals in Green's function extraction and the generalized optical theorem. Physical Review E, 78(3), p.036606.

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