A study of ambient seismic noise as the source for body-wave interferometry

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One application of seismic interferometry is the extraction of Green's functions from ambient noise. Theory tells us that if uncorrelated noise sources illuminate the recording stations from all directions and if the noise can be characterized as a random process, then the complete Green's function, including the body-wave reflection response and surface waves, is retrieved from a crosscorrelation-and-summation operation (Wapenaar, 2004). Fixing one receiver at a time, correlating the trace from that receiver with every other trace, and summing over the recording time, a virtual source is synthesized at the fixed receiver location and recorded by the other traces. If the noise is generated mainly by sources at or close to the Earth's surface, then only the surface-wave part of the Green's function can be extracted with the crosscorrelation-and-summation operation. The latter is the case, for example, in many global and regional studies of surface-wave tomography with ambient noise when energy in the primary and double-frequency microseism bands, approximately between 0.07 Hz. and 0.5 Hz., is used for correlations. While many papers show successful application of ambient seismic noise-interferometry for surface waves several issues remain with this method. One of the main problems is related to the spatial distribution of the noise sources (Yang and Ritzwoller, 2008) that synthesize the virtual source. It is well known that an uneven illumination causes a directionally biased Green's function (Paul et al., 2005), or even unphysical events.

All energy registered by receivers is potentially input for the crosscorrelation-and-summation process, synthesizing the virtual source. By manipulating this energy (for example by bandpass filtering or time-windowing), one can manipulate the virtual source. For example, rather than looking at continuous noise records, one could select deterministic events (Yao et al., 2009) or select coda energy (Paul et al., 2005). The advantage of this approach is that the distribution of deterministic events is easier to evaluate. In certain cases, the impact on the crosscorrelation result may even be predicted (Ruigrok et al., 2009). The approach in Ruigrok et al. (2009) bears resemblance to the virtual-source method, as developed in the seismic exploration industry (Bakulin and Calvert, 2006). In the virtual-source method, however, one can optimize the source distribution along the surface to create a desired virtual source. When using continuous noise sources, this is practically unfeasible.

In seismic exploration, one is particularly interested in body-wave reflections, as they provide the highest resolution images of potentially hydrocarbon bearing structures. However, the extraction of body-wave reflections using ambient-noise interferometry has turned out to be much more challenging than the extraction of surface waves from noise. This is in part due to the longer propagation paths between the receivers (and the higher rate of geometric spreading), the more severe restrictions on the distribution of sources for the retrieval of body waves (as pointed out by Wapenaar, 2004, for the retrieval of reflections, sources should be located in the subsurface) and the fact that omnipresent surface-wave noise dominates the generally weaker body-wave noise. In fact, for body waves it is less clear whether any (continuous) noise sources contribute to the synthesis of Green's functions and if any, what are the source mechanisms and distributions.

Most studies on noise observations agree that the bulk of the noise recorded at the surface of the Earth consists of fundamental- and higher-mode surface (Rayleigh) waves. Nevertheless, comparisons of spectra measured at the surface and in boreholes also permit the alternative explanation of (standing) body waves (Gupta, 1965, Seriff et al., 1965, Douze, 1967). Only very few studies have observed directly and with confidence the presence of body waves in noise. If any, they appeared to be relatively low-frequency body waves, probably excited by oceanic microseisms (Toksöz and Lacoss, 1968). In the frequency band of interest for seismic exploration (> 1 Hz), these observations are particularly rare.

Nevertheless, at the hand of an example with data recorded in a relatively quiet area, Draganov et al. (2007) showed it was possible to extract body-wave reflections from ambient seismic noise. Because of the specific acquisition geometry used in this experiment, it was only possible to confirm the possible presence of body waves in the raw noise records by examining the polarization of vertically traveling waves (Draganov et al., 2006).

The experiment was repeated on a much larger scale using a 3-D exploration-seismic acquisition spread by Shell in Libya (SEPLG) in 2007. The extent of the entire array on which the noise was simultaneously recorded allows more flexibility in spatial processing. In addition, it allows us to take advantage of the specific geophone-group geometry as it was designed to enhance body waves while suppressing surface waves at specific wavenumbers (as already suggested by Baskir and Weller, 1975). Draganov et al. (2009a,b) applied seismic interferometry and standard seismic processing to these data to extract seismic reflection images from ambient noise.

In this abstract we discuss work in progress on the characterization of roughly 11 hours of ambient seismic noise recorded on approximately 3000 receiver channels during an exploration survey in the Sirte Basin, East of Ajdabeya in Libya. We pay particular attention to the composition of the noise wavefield and its implications for body-wave interferometry.

Survey geometry and data

In September 2007, Shell recorded approximately 11 hours of ambient seismic noise during an exploration survey in the Eastern part of the Sirte Basin near Ajdabeya in Libya. The recording geometry is shown in Figure 1.

Libya is not generally considered an active seismic area, although several large earthquakes have occurred in the past. The most active part is the Eastern flank of the Hun graben, on the western part of the Sirte Basin. The eastern part of the basin is quieter, with no activity in the basin itself (Suleiman and Doser, 1995). The Cyrenaica platform – to the NE of the survey area -- is also an area of recent seismicity. Not much is known about the specific characteristics of ambient seismic noise in Libya, since only few seismometers have been deployed in the past.

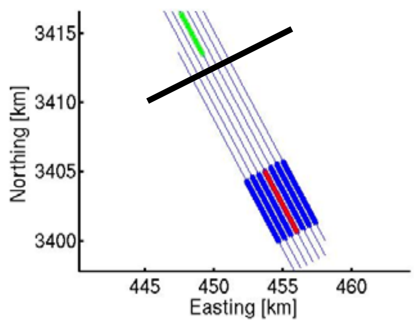

Figure 1. The geometry of the passive survey (thin lines) and approximate location of the road. Parts of the recording spread used for frequency-wavenumber analysis are indicated by the fat blue lines and red and green crosses.

The recording equipment used in this survey, consisted of groups of standard 10 Hz vertical-component geophones and a Sercel 304S recorder. The channels on the line were connected to patterns consisting of 48 geophones. These patterns are designed to suppress the surface wave generated by the vibrator in active seismic surveys, while passing body-wave reflections with much higher apparent velocities.

Unfortunately, the equipment does not allow a full characterization of the ambient noise below a few Hz. Because of this, we have not attempted to quantify the noise in terms of absolute displacements and compare them with the standard noise models. The geophone response of a standard 10 Hz geophone is usually not adequate to record very low-amplitude signals because of 1) its relatively low sensitivity and 2) the 12 dB/Oct decay below 10 Hz.

Nonetheless, we see a strong response down to about 1 Hz. This can partly be attributed to the fact that for each geophone station, the 48 geophones from the pattern are summed together, thereby boosting the signal. Also, the double-frequency microseism starts to ramp up at the low-frequency end.

Noise at short periods is usually attributed to local conditions such as atmospheric conditions and human-generated noise. In our case, a traffic road intersects the survey area, generating strong surface-wave noise. Figure 2 shows the power spectral density (PSD) estimates for all traces along a line in the middle of the survey area. These spectra were calculated using Welch's method. We used approximately 2 hours of noise split up in 47 s windows (the record lengths) with 50 % overlap. Most of the noise is concentrated below approximately 6 Hz. The road can be identified by an increase in amplitude of the noise, which is evident especially at the frequencies up-to about 20 Hz, around 14 km along the line.

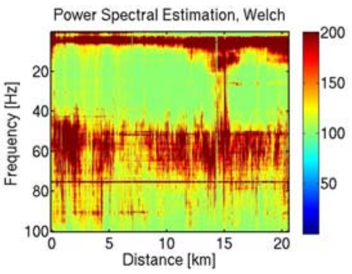

Figure 2. PSD of continuous noise for each receiver station along one line in the survey.

In order to investigate the directionality of the noise, due to the presence of the road, we determine frequency-wavenumber (FK) spectra. Because the crossline sampling of the array is not sufficient to obtain an unbiased two-dimensional FK spectrum for the expected low surface-wave velocities, we determined the one-dimensional FK spectra on either side of the road (Figure 3). The estimated (FK) spectrum essentially shows the spatial correlation of the noise. The left panel of Figure 3 is the FK spectrum for the part of the line indicated with the red crosses in Figure 1. Considering the negative wavenumbers, the energy comes from the North. The right panel shows the FK spectrum for the part of the line indicated by the green crosses. The wavenumbers are positive indicating the energy propagates to the North. This confirms that the main source of energy is indeed the road. The spread in apparent velocities in these spectra can have two reasons: 1) frequency-dependent velocities (dispersion) and 2) energy arriving at the receiver line from directions other than along the line connecting the receivers. In the next section, we use this energy as the source for surface-wave interferometry.

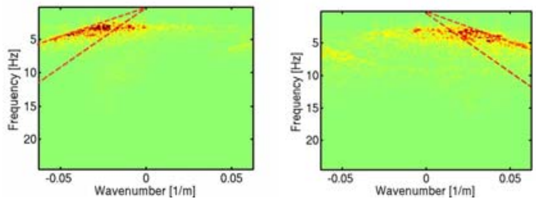

Figure 3. FK spectrum of the noise on the left side of the road and the right side of the road.

Surface waves from noise

Our goal is to apply seismic interferometry to the data, with an emphasis on extracting possible body (P) wave reflections. Wapenaar and Fokkema (2006) derive a representation that expresses the Green function as a sum of correlations of observed traces. As stated in the introduction, we extract a virtual-shot record by fixing one trace and correlating this trace with other traces (along a line, or between lines) and summing the resulting correlograms. We first apply this processing to the data in the frequency band 2 to 25 Hz.

The result is shown in Figure 4. Because of the uni-directionality of the noise (see previous paragraph), we added the anti-causal Green's function to the causal part. It is clear that a strong surface wave dominates this record. In Figure 4 we also show the dispersion curve extracted from the passive data, combined with the dispersion curve extracted from the active data. The passive part (below 5 Hz) shows good agreement with velocities obtained in the FK spectra in the previous section. The combined curve shows the velocities from the active and passive dispersion curves match well. Note that the active part of the dispersion curve is severely degraded due to the use of the geophone patterns, which are aimed at suppressing surface waves. The (combined) dispersion curve can be inverted to extract depth-dependent velocity profiles or can be used in surface-wave tomography.

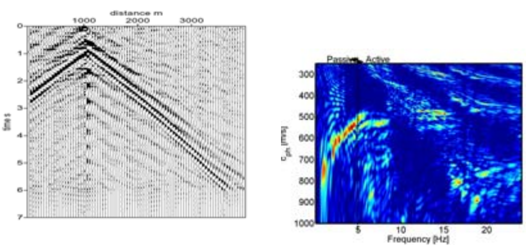

Figure 4. Surface wave extracted from noise (anti-causal and causal part summed) and dispersion curve extracted from the record.

So far, this demonstrates that we can use the surface-wave noise to extract information about the shallow subsurface. In the next section, we examine what energy contributes to the synthesis of the body-wave Green's function and show a virtual source record containing reflections extracted from the noise.

Body wave reflections from ambient noise

The panel on the left-hand side (LHS) of figure 5 shows a representative record of continuous noise after band-pass filtering to suppress the main surface-wave noise. Apart from some remaining surface-wave noise (the inclined events), there does not appear to be any other coherently aligned energy. In order to extract reflections with seismic interferometry, theory tells us we should have noise sources radiation from the deeper subsurface. Hence, we need (nearly) vertically travelling energy. Even if this energy were present in the continuous noise, we would have to stack over very long recording times to be able to extract such weak coherent energy. Since we only have 11 hours of recordings available, we can also opt for an alternative approach and search the noise-records in more detail for visually discernable 'events', travelling nearly vertically. The right-hand side (RHS) panel of Figure 5 shows part of a band-pass filtered record with such an event. Only part of the receiver line indicated by the thicker lines in Figure 1 is shown here. In order to compare the composition of the first panel to the second, we first calculate the power spectrum of the record with 'event' and the spectrum of two hours of noise records (which could include events). Figure 6 shows the spectrum of two panels with events and the average spectrum of 2 hours of noise. The frequency bands are not very different, but distribution and amplitude of the energy is significantly different for the events. In order to further characterize these events, we form their FK spectra using beamforming.

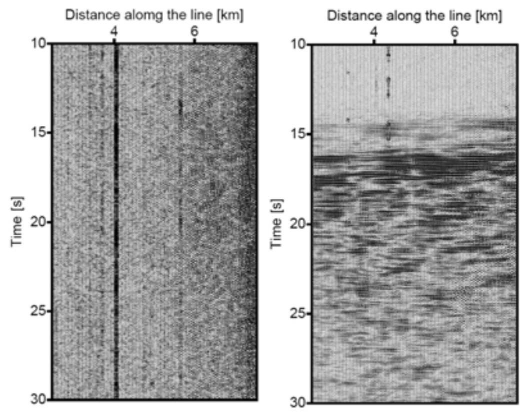

Figure 5. Records along the same part of one receiver line. The left-hand side panel shows part of the continuous noise. The right-hand side panel shows an isolated 'event'.

At low wavenumbers, the array indicated by the fat blue lines in Figure 1, produces a reliable FK spectrum, as shown for a plane wave with apparent velocity of 8.5 km/s and back-azimuth 30 degrees in the RHS of Figure 6. The FK spectrum is shown in a polar plot with slowness along the radius and back-azimuth along the circumference. Figure 7 shows the FK spectra of two actual events. The slowness range in the plot is ~ [5e-5 3.3e-4] s/m. The high apparent velocities correspond to upcoming body waves. It is as yet unclear what is the origin of these waves, but with the analysis of more events and investigating the directions of approach, we hope to be able to say something about their origin.

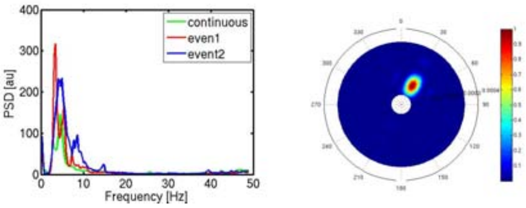

Figure 6. Spectrum of approximately 2 hours of continuous noise (green line), and of 2 isolated events (red and blue lines). All spectra were averaged along the line between receiver station 50 and 150.

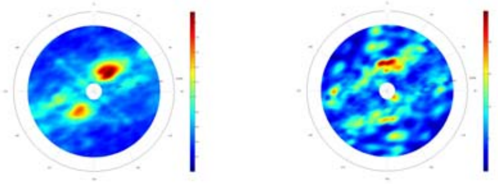

Figure 7. FK- power spectrum for the 'event' shown in Figure 6 (bottom), summed over the frequency band [3 10] Hz. The spectrum clearly shows a plane wave with apparent velocity of approximately 8.7 km/s. The right panel shows the FK spectrum of another 'event'. The apparent velocity of this event is approximately 7.5 km/s.

Correlating and summing all noise records (11 hours), results in the record shown on the LHS of Figure 8, with the virtual source at 1 km. The right panel shows a record from the active survey with the active source at the same location. (Note that some shot processing has been applied to both records to remove remaining surface waves, for example.) Several hyperbolic events coincide, showing we have extracted body wave reflections. Currently, we are extracting all 'events' and plan to correlate only the records with such events. We expect that the body wave reflections will be better resolved this way.

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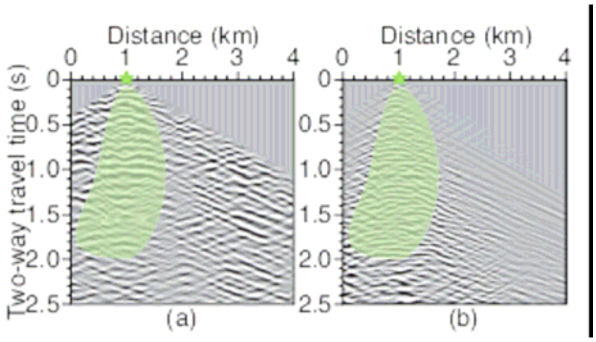

Figure 8. The left panel is a virtual shot record obtained from ambient seismic noise. The right panel shows the shot record from an active source at the same location.

Conclusions

We investigated some properties of seismic noise recorded for 11 hours in the eastern part of the Sirte basin in Libya. The bulk of the energy in the noise is composed of surface waves at frequencies below 5 Hz. Using this part of the noise for interferometry results in the extraction of surface waves with velocities that match well with the velocities extracted from the active dispersion curve. Correlating 11 hours of filtered noise records results in the extraction of shot records containing body-wave reflections that coincide with reflections in an active shot record. From a more detailed analysis of the noise, we identified several records containing coherent energy traveling nearly vertically. FK analysis of these events show that they have very high apparent velocities, corresponding to upcoming body (P-) waves. Current work is focused on further characterizing these events. We will also selectively correlate the noise using only the 'events'. We expect this will enhance the body-wave reflections in the virtual-shot records. Characterization of the events will allow us to evaluate the effects of their distribution on the resulting virtual-shot records.

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