Retrieval of reflections from seismic background-noise measurements

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[1] The retrieval of the earth's reflection response from cross-correlations of seismic noise recordings can provide valuable information, which may otherwise not be available due to limited spatial distribution of seismic sources. We cross-correlated ten hours of seismic background-noise data acquired in a desert area. The cross-correlation results show several coherent events, which align very well with reflections from an active survey at the same location. Therefore, we interpret these coherent events as reflections. Retrieving seismic reflections from background-noise measurements has a wide range of applications in regional seismology, frontier exploration and long-term monitoring of processes in the earth's subsurface. **Citation:** Draganov, D., K. Wapenaar, W. Mulder, J. Singer, and A. Verdel (2007), Retrieval of reflections from seismic background-noise measurements, *Geophys. Res. Lett.*, *34*, L04305, doi:10.1029/2006GL028735.

1. Introduction

[2] One of the goals in seismology is to obtain an image of the earth's interior. The construction of a good image requires a regular and dense distribution of seismic sources. In regional and global seismology, where mostly earthquakes are used as seismic sources, this distribution is limited mainly to active faults. Furthermore, the earthquakes primarily provide transmission information, which prevents the use of reflection imaging methods. In exploration seismology, the increased demand for oil and gas pushes the exploration activities to new frontier areas, where no previous exploration activities have taken place, and sometimes to areas where no conventional seismic sources, such as seismic vibrators and dynamite, can be used. The limitations on the distribution of seismic sources on global and regional scale as well as the desire for cheaper exploration methods have motivated researchers to look for alternatives. One such alternative is the retrieval of the reflection response from the correlation of seismic background noise. Here the terminology 'seismic background noise' is used in a broad sense: it refers to random noise as well as transient events coming from a distribution of sources with unknown positions, source signals and time origins. The idea to use background noise for retrieval of the reflection response finds its roots in early work of *Claerbout* [1968]. He showed that for a horizontally layered medium the auto-correlation of the transmission response of a seismic noise source in the subsurface yields the reflection response. Later, he conjectured for a 3-D inhomogeneous medium that by cross-correlating noise traces recorded at two locations on the surface, one can retrieve the wave field that would be recorded at one of the locations if there were a source at the other. This idea was first tested in the field in the 1970's for exploration seismology, but results were inconclusive [*Baskir and Weller*, 1975]. In the 1980's and 1990's, several researchers applied the auto-correlation method to specifically selected low-magnitude earthquakes, recorded at several stations [*Scherbaum*,1987; *Daneshvar et al.*, 1995]. The advantage of using earthquakes is that their hypocenters and time origins are (approximately) known so that one can make a targeted selection. The pseudo-reflection seismograms obtained from the auto-correlation were inverted and compared to impedance and velocity models from the same areas. The comparison showed reasonable agreement and was encouraging. The application of the cross-correlation method to helioseismic data successfully retrieved time-distance curves at the surface of the sun [*Duvall et al.*, 1993].

[3] Recently, researchers derived relationships for the retrieval of the seismic impulse response (Green's function) from cross-correlations of diffuse fields [*Weaver and Lobkis*, 2001; *Wapenaar et al.*, 2002; *Derode et al.*, 2003; *van Tiggelen*, 2003; *Snieder*, 2004; *Wapenaar*, 2004] and of controlled-source experiments [*Schuster*, 2001; *Wapenaar et al.*, 2002; *Bakulin and Calvert*, 2004]. Such methods, that use correlation to retrieve the Green's function, are now united under the term "Seismic Interferometry". The term interferometry is borrowed from radio astronomy, where it refers to cross-correlation methods applied to radio signals from distant objects. Cross-correlation of diffuse coda waves in Mexico [*Campillo and Paul*, 2003] and of ambient seismic noise observed at seismological stations in South California [*Shapiro et al.*, 2005] resulted in the successful retrieval of surface waves between the stations. *Roux et al.* [2005] also used ambient seismic noise and could retrieve not only surface waves, but also turning P-wave arrivals.

[4] Theory predicts that not only surface waves and turning waves can be retrieved by cross-correlation, but body wave reflections from layer interfaces (primaries as well as multiples) can be retrieved as well [*Wapenaar*, 2004]. This confirms Claerbout's conjecture for a 3-D inhomogeneous medium. Reflected body waves contain information about the subsurface that is essentially different from that contained in surface waves and turning body waves, in particular with respect to spatial resolution.

[5] Here we show results of the retrieval of the earth's reflection response from the cross-correlation of about ten hours of seismic background noise.

2. Passive Data Set

[6] The data we used for cross-correlation were recorded in 2005 by SRAK with Shell's technical advice and support.

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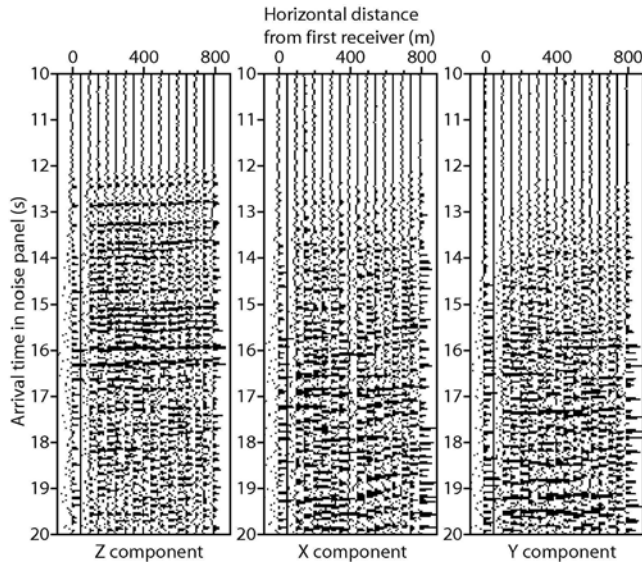[2]Shell International Exploration and Production, Rijswijk, Netherlands.

Figure 1. Ten seconds of seismic background noise (filtered between 2 and 10 Hz) from one of the 70-seconds noise panels as recorded by the vertical (Z), the horizontal in-line (X) and the horizontal cross-line (Y) components of the geophones. Starting at about 12 s one can see coherent arrivals with very high apparent propagation velocity resulting from body-wave arrivals.

The experimental set-up consisted of 17 standard exploration three-component geophones arranged in a single line. The geophone spacing was 50 m and the time-sampling rate was 4 ms. The passive array was planted in a desert area so that during the recording of the background noise the cultural noise would be minimal. An active seismic survey was available along the line of the passive array, allowing for verification of the retrieved reflections. The acquisition equipment allowed for a continuous recording of noise for 70 s. The recording was then interrupted for 30 s to store the already acquired data, after which the recording continued. This resulted in 523 records of 70 seconds each, amounting to about ten hours of seismic background-noise data.

3. Retrieval of Reflections From Seismic Noise

[7] For retrieval of the reflection response from the recorded seismic background noise, we used the relation

$$\left\{ G_{z,z}(\mathbf{x}_A, \mathbf{x}_B, t) + G_{z,z}(\mathbf{x}_A, \mathbf{x}_B, -t) \right\} * S(t)$$
$$= \langle v_z(\mathbf{x}_A, -t) * v_z(\mathbf{x}_B, t) \rangle. \quad (1)$$

[8] The right-hand side denotes the cross-correlation between the observed seismic background-noise traces $v_z(\mathbf{x}_A, t)$ and $v_z(\mathbf{x}_B, t)$ at points $\mathbf{x}_A$ and $\mathbf{x}_B$, respectively (v_z denoting the vertical component of the particle velocity; other components could be considered as well). The background noise is assumed to be caused by a distribution of temporally uncorrelated noise sources in the subsurface. The angle brackets denote an ensemble average, which in practice is approximated by averaging over the different time windows. On the left-hand side we have the Green's function $G_{z,z}(\mathbf{x}_A, \mathbf{x}_B, t)$ and its time-reversed version $G_{z,z}(\mathbf{x}_A, \mathbf{x}_B, -t)$, representing the observed vertical particle velocity

at a geophone at point $\mathbf{x}_A$ as if there were a vertical force source at point $\mathbf{x}_B$. These Green's functions are convolved with the auto-correlation of the noise sources in the subsurface. When the geophones at $\mathbf{x}_A$ and $\mathbf{x}_B$ are illuminated by uncorrelated noise sources from all directions, the use of equation (1) will allow the retrieval of the complete Green's function (surface waves, reflections, refractions, multiples, etc.) and its time-reversed version. When the illumination is asymmetric, we may need to average the retrieved Green's function and its time-reversal to compensate for the incomplete illumination.

[9] As mentioned above, the passive seismic array recorded 523 noise panels. Even though the recorders were sensitive to frequencies between 1 and 80 Hz, we found that the useful information was concentrated between 2 and 10 Hz. In this frequency band, the noise panels show mainly random noise and propagating energy in the form of weak surface waves (the amplitudes of these surface waves are of the same order as those of the random noise). After cross-correlation, these events will contribute to the retrieval of the surface wave part of the Green's function. Among the 523 noise panels, there were 35 panels in which we could recognize coherent arrivals with very high apparent propagation velocity. Figure 1 shows the three components of a part of one such 70-seconds noise panel in the frequency band between 2 and 10 Hz (note that the trace at 50 m is zero since the geophone at that position was not functioning). On the vertical component (Z) we observe a nearly horizontal arrival starting at about 12 seconds. Because this arrival is absent on the horizontal components (X and Y), we interpret it as propagating energy due to body P-waves from deeper sources, vertically below the passive array. After cross-correlation, this type of events will contribute to the retrieval of reflections from the subsurface layers. Most of the nearly horizontal coherent events have amplitudes in the order of the background noise in the other panels (the random noise and the surface waves). Only two panels exhibited nearly horizontal arrivals with much stronger amplitudes. The panel with the strongest amplitudes, approximately 100 times stronger than the background noise in the other panels, is the one shown in Figure 1. We compared arrival times of body waves from available information of earthquakes on a global scale (M > 1.9) with the arrival times of the events in Figure 1, but failed to see any correlation. This makes us think that the nearly horizontal events are caused by some local subsurface sources.

[10] In order to retrieve the response that would be recorded by the passive array of geophones when there would be a source at the position of the first geophone, we used the following procedure. Since the amplitude of the noise in the different noise panels varies significantly, we energy-normalized each noise panel separately. Then we extracted the first trace from each noise panel and correlated this trace with all the other traces in the same panel. This resulted in 523 so-called correlation panels, which were subsequently summed. The summation result was then band-pass filtered between 2 and 10 Hz to obtain a so-called common-source gather with retrieved source position at the position of the first geophone. The above procedure was repeated in such a way that we retrieved source positions at all the geophone positions of the passive array (16 in total; recall one geophone was not functioning).
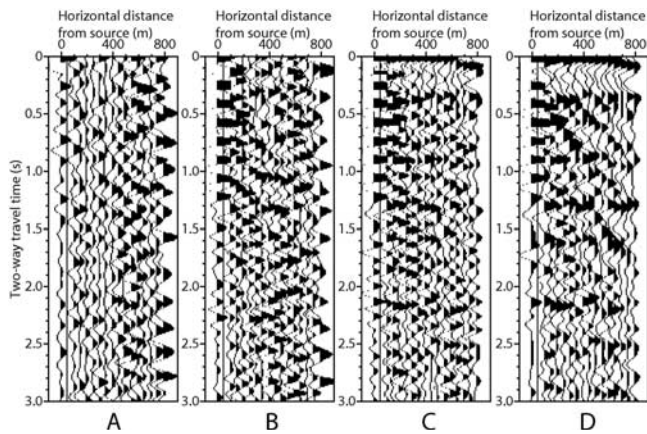
Figure 2. Gradual build-up of a common-source gather with a retrieved source position at 0 m (the position of the first geophone in the background-noise experiment) after correlation of (a) 70 s, (b) 1 hour, (c) 4 hours, and (d) 10 hours of seismic background noise.

[11] By using more noise panels for correlation, we effectively use longer background-noise recordings. Figure 2 shows the gradual build-up of the common-source gather when correlating increasingly longer background-noise recordings. We observe that the amount of coherent events increases when summing an increasing number of noise panels (i.e., with increasing recording time). This is due to the fact that with longer recording times we capture more propagating seismic energy. Moreover, the underlying assumption that the background-noise sources are uncorrelated is better fulfilled with longer recording times. Figure 2d shows the retrieved common-source gather with a retrieved source position at 0 m after correlation and summation of all 523 noise panels. On this retrieved common-source panel we can identify several coherent arrivals. The inclined coherent event, starting at 0 s at zero source-receiver distance (offset) and ending in the range of 0.9 to 1.8 s at the maximum offset, is interpreted as a dispersive surface wave. Such inclined events are present in all retrieved common-source gathers. Figure 2d also shows several coherent nearly horizontal events. The events at around 0.3 s, 0.9 s, 1.25 s, and 2.15 s might be retrieved reflections and result from correlation of the nearly horizontal events, like the ones in Figure 1, present in the background-noise data.

[12] To evaluate the quality of the results, we compared the retrieved common-source gathers with data from an active seismic reflection survey acquired at the same location. The active survey was carried out a short time before the background-noise experiment. The active survey used seismic vibrators as sources at the surface and single vertical component geophones as recorders with a geophone spacing of 25 m; the largest source-receiver offset was much larger than the one in the passive array. The comparison of the retrieved common-source gather with the active survey common-source gather is not trivial. One problem is that the frequency content of the two data sets is different. In the active reflection data, the propagating energy was concentrated between 10 and 50 Hz, while the frequency band of the propagating energy in the background-noise data was between 2 and 10 Hz. As a result, separate events recorded

short after one another in the active survey may appear as a single event in the retrieved common-source gathers. The surface waves in the active reflection survey are concentrated in the frequency band up to 20 Hz. This made it easier to compare them with the retrieved inclined coherent events in the retrieved common-source gathers. The conclusion is that the inclined coherent events are indeed retrieved surface waves arrivals. But we are more interested to see if we have retrieved reflection arrivals. The comparison of the retrieved nearly horizontal coherent events, like the ones at around 0.3, 0.9, 1.25 and 2.15 s in Figure 2, with reflection hyperbolae in the active data is more difficult. This is due to the different frequency bands, the different quality of the retrieved nearly horizontal coherent events in the different retrieved common-source gathers, and the fact that in the raw active common-source gathers the reflection hyperbolae are not easily observed.

[13] To improve the clarity of reflection arrivals in both data sets, we performed the following processing steps. At the location of the passive array the subsurface geology consists of nearly horizontal layers. This means that for the short distances considered we can assume the subsurface to be horizontally layered. With this assumption in mind, we resorted the traces in the 16 retrieved common-source gathers into common-offset panels. Next, the traces in each common-offset panel were summed and normalized for the number of summed traces, producing a single output trace per common-offset panel. The output traces from the different common-offset panels were sorted into a so-called common-offset stack panel (Figure 3a). The same procedure was applied to the active data using 17 common-source gathers with source positions around the corresponding locations of the geophones from the passive array. The resulting common-offset stack panel was further filtered in the frequency-wave number domain (f-k filtering) to eliminate the surface waves and then band-pass filtered between 13 and 33 Hz (Figure 3b). As a result of this processing, the individual coherent events have been strengthened, albeit at the expense of some loss of resolution. This allowed us to compare the arrival times of the coherent events in Figure 3a with the reflection hyperbolae in Figure 3b. The red lines connect the retrieved events in Figure 3a to reflection hyperbolae in Figure 3b and the green vertical lines in Figure 3b show the maximum offsets that are covered by the passive array and shown in Figure 3a. There is a very good arrival-time agreement between the three retrieved events indicated by the red lines and the corresponding reflection hyperbolae in the active data. The earlier two events can be traced to agree with hyperbolae in the offset region between the green lines, as well as outside them. Only the latest retrieved coherent event is to be related to a reflection event at the lower left and lower right parts in Figure 3b outside the passive array offsets.

[14] Still the retrieved surface waves in Figure 3a hamper the good comparison between the two datasets. Due to the very narrow frequency band of the retrieved data, we did not use an f-k filter to eliminate the retrieved surface waves, but chose to suppress the inclined coherent events in a different way. By simply summing the retrieved common-source gathers we created the response of a line source along the passive array, see Figure 3c (in exploration seismology, this operation is called a brute stack). Note that
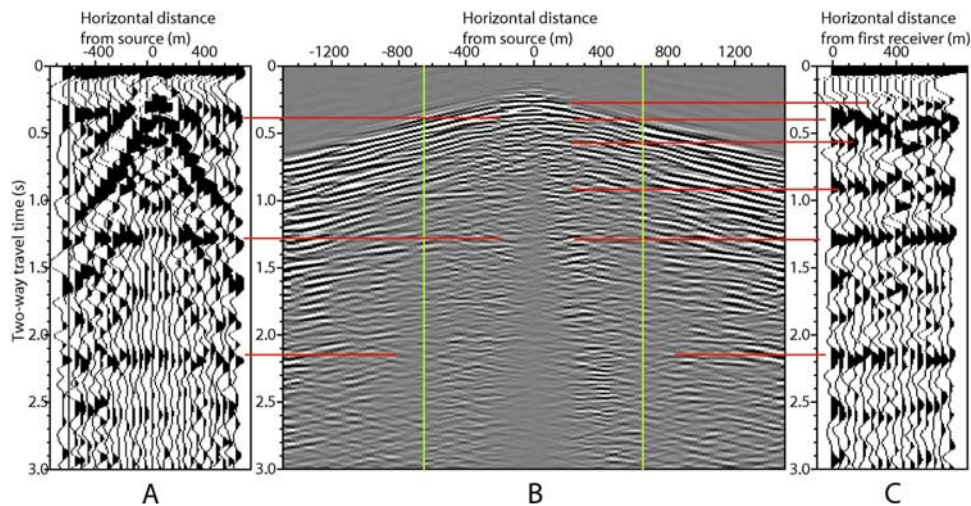
Figure 3. (a) Common-offset stack panel obtained from the common-source gathers retrieved from the passive data. (b) Common-offset stack panel obtained from the common-source gathers from the active data after surface-wave elimination and band-pass filtering between 13 and 33 Hz. (c) Line-source response obtained by summing the common-source gathers retrieved from the passive data (brute stack). Red lines indicate travel-time comparison between events retrieved from the passive data and reflection hyperbolae in the active data. Vertical green lines indicate the range of offsets in the passive array.

horizontal arrivals are enhanced whereas the inclined arrivals are suppressed. The comparison of the retrieved horizontal events in Figure 3c with the reflection hyperbolae in Figure 3b is now even easier – the retrieved coherent events show very good arrival-time agreement with the reflection hyperbolae in the active data. This makes us conclude that the retrieved coherent events in Figure 3c are retrieved reflection arrivals.

4. Conclusions

[15] Previous experiments have shown that cross-correlation of passive measurements of seismic background noise results in the retrieval of surface waves and turning body waves between the different stations. Theory predicts that the cross-correlation should result in retrieval of the full Green's function, including reflections, refractions, multiples, etc. We showed that this is indeed possible. We correlated ten hours of recorded seismic background noise, which resulted in the retrieval of several coherent events. The comparison of the retrieved events with active exploration data along the same line confirmed that we have retrieved reflection arrivals. The retrieval of reflections from the correlation of seismic background noise has promising applications in regional seismology, frontier exploration and long-term monitoring of processes in the earth's subsurface.

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