Z038

Subsurface Structure from Ambient Seismic Noise

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SUMMARY

One of the applications of seismic interferometry (SI) by cross-correlation is the retrieval of the reflection response of the subsurface from ambient seismic noise recorded at the surface. We apply SI to ambient-noise data recorded in a desert area in North Africa. The retrieved results show distinct coherent events with hyperbolic moveout. We compare the retrieved results with results from an active reflection survey recorded at the same location. We apply standard seismic processing to the retrieved results and obtain a stacked time-migrated reflection profile of the subsurface.

Introduction

In recent years, the interest for Seismic Interferometry (SI) has substantially grown in both industry and academia. An extensive overview of the paths and applications can be found in Wapenaar *et al.* (2008) and Schuster (2009). One of the applications of SI is the retrieval of the Earth's reflection response from the cross-correlation of ambient seismic noise recorded at the Earth's surface. This technique was first proposed by Claerbout (1968) for a 1D medium. He showed that the auto-correlation of the transmission response can retrieve the reflection response of the medium. Later, he conjectured that in the case of a 3D acoustic medium to retrieve the reflection response, one should cross-correlate the transmission responses observed at the surface. Wapenaar *et al.* (2002) and Wapenaar (2004) proved Claerbout's conjecture for any 3D inhomogeneous acoustic as well as elastic medium making use of wavefield-reciprocity theorems. Actually, the developed theories show that cross-correlating the recorded noise will retrieve the complete Green's function of the medium.

The process of retrieval of the Green's function from the cross-correlation of recorded noise has been extensively investigated using modelling results. The method was successfully applied to the retrieval of surface waves (Campillo and Paul, 2003; Shapiro *et al.*, 2005) and is now becoming a standard application in seismology. The retrieval of reflections has proved more elusive. Only recently, Draganov *et al.* (2007) showed that reflections can indeed be retrieved. In the following, we present results from the application of SI to ambient-noise data recorded in North Africa with the aim to retrieve the reflection response, which can then be subjected, as for active data, to velocity analysis, stacking, and migration to obtain time sections of the subsurface.

Description of the field experiment

In 2007, Shell carried out a passive seismic acquisition experiment in a desert area in North Africa. The objective was to record ambient seismic noise and to apply SI to it. The field geometry consisted of an areal array of 8 parallel lines with about 400 receiver positions on each line. The spacing between the lines was 500 m and the spacing between neighbouring receiver stations was 50 m. Each receiver position represented a group of 48 industry-standard 10-Hz vertical-component geophones. The time sampling was 4 ms. The 2D array recorded in total about 11 hours of ambient noise. Due to field-hardware restrictions, the noise was split and stored in 47-seconds-long windows (ambient-noise panels). The 2D passive array also formed part of an active seismic reflection survey, which was shot at the same locations.

Retrieval of the reflection response

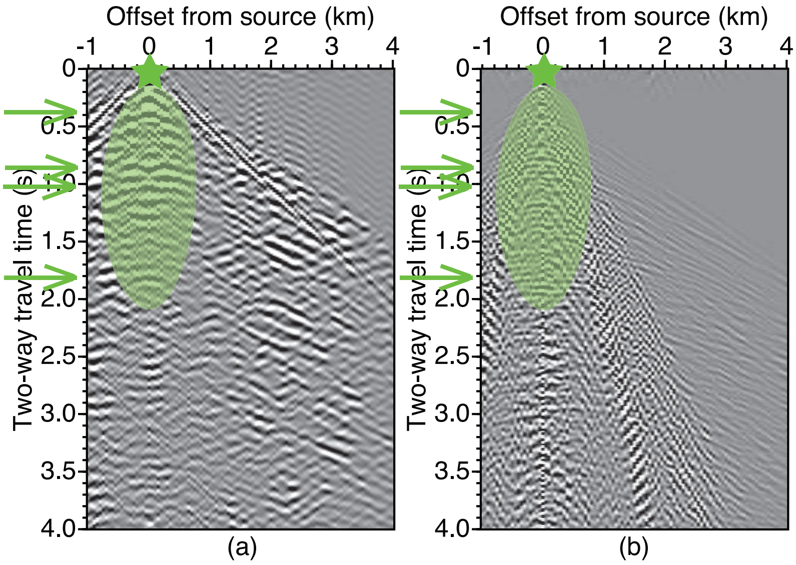
To retrieve the reflection response from the recorded ambient-noise data, we use the SI relation as derived in Wapenaar (2004). In the frequency domain, this relation reads

$$2\Re\left\{\hat{G}^{\nu,t}_{p,q}\left(\mathbf{x}_A,\mathbf{x}_B,\omega\right)\right\}\hat{S}\left(\omega\right) \approx \left\langle \left\{\hat{\nu}^{obs}_{p}\left(\mathbf{x}_A,\omega\right)\right\}^{*} \hat{\nu}^{obs}_{q}\left(\mathbf{x}_B,\omega\right)\right\rangle , \tag{1}$$

where $\hat{G}^{\nu,t}_{p,q}\left(\mathbf{x}_A,\mathbf{x}_B,\omega\right)$ is the Green's function observed at point $\mathbf{x}_A$ due to a source at point $\mathbf{x}_B$, $\hat{S}\left(\omega\right)$ denotes the power spectrum of the recorded ambient noise, and $\Re$ stands for taking the real part of a complex function. The Green's function represents the observed p-component of the particle velocity ν due to a traction source (t) acting in the q-direction ($p,q=1,2,3$). As both the source and receiver are at the surface, the Green's function will contain the reflection response of the medium. At the right-hand side of relation (1), $\langle\cdot\rangle$ stands for spatial ensemble average and $\hat{\nu}^{obs}_{p(q)}\left(\mathbf{x}_{A(B)},\omega\right)$ denotes the observed $p\,(q)$-component of the particle velocity that will be measured at the surface at $\mathbf{x}_{A(B)}$ due to subsurface noise sources. Relation (1) states that the cross-correlation (in the time domain) of the ambient noise recorded at two stations at the surface approximates the Green's function and its anti-causal version at one of the stations as if a transient source were located at the other station. In practice, the ensemble average is approximated by averaging over different time windows.

In the following, we show results from the application of SI to ambient-noise data recorded along one of the receiver lines. This line has 412 receiver-station positions at 50 m spacing. The recorded ambient noise is dominated by strong remnants of spatially coherent surface waves that were not suppressed by the geophone groups. These surface waves are excited randomly in time by traffic along a road that crosses the line at approximately 14 km. As we aim to retrieve reflections, the surface waves should be further suppressed. Frequency and frequency-wavenumber (f-k) analysis revealed that the most energetic part of the surface waves is mainly concentrated below 6 Hz. Furthermore, the amplitude frequency spectrum of the ambient noise shows significant spectral notches and peaks above 24 Hz, which may complicate our analysis. Therefore, for further processing, we select the energy between 6 and 24 Hz with a band-pass filter. We then apply an f-k filter to remove the surface waves that were not suppressed by the geophone groups.

Following relation (1), we correlate the vertical components of the filtered ambient noise to retrieve the vertical component of the particle velocity that would result from a vertical traction source. We thereby use the following procedure. We take one filtered ambient-noise panel and energy-normalise it. Then, we extract one of its traces (a master trace at $\mathbf{x}_B = 1$ km) and cross-correlate it with this ambient-noise panel to obtain a so-called correlation panel. We repeat this process for all 47-seconds ambient-noise panels recorded along the line while always taking the master trace to be at the same location. The resulting ≈ 900 correlation panels are then summed together to obtain a retrieved common-shot gather. Due to the energy normalisation of the ambient-noise panels, all the correlation panels in the summation process contribute to the final result. The retrieved gather is deconvolved with a wavelet obtained by applying a narrow window around zero time to the auto-correlated master trace (in our example the trace at horizontal position 1 km). As a last step, the retrieved causal and anti-causal parts are summed together. The final retrieved result for a master trace at 1 km is shown in Figure 1(a).



(a)

(b)

Figure 1: Comparison between **(a)** a common-shot gather retrieved from the ambient noise and **(b)** a common-shot gather from the active reflection survey recorded at the same location. The green stars indicates (virtual) shot positions. The green arrows and areas highlight hyperbolic events that coincide in time.

The retrieved common-shot gather exhibits several coherent events. We compare the retrieved result to a common-shot gather from the active reflection survey at the same location. The active reflection data was shot using seismic vibrators and as a result the active survey contains reflections up to higher frequencies. For comparison reasons, the active reflection data is also band-pass filtered between 6 and 24 Hz (Figure 1(b)). Comparing the two shot gathers we see that the retrieved coherent arrivals correlate very well in a travel-time sense with the reflection hyperbolae in the active data (see the arrows and the areas highlighted in green). The retrieved shot gather is not of the same quality as the active shot gather for several reasons. One reason is that, in order to obtain a complete retrieval of the Green's function, including the reflection response, the passive receiver line should be illuminated by subsurface noise sources from all directions. When this is not the case, the Green's function retrieval might not be complete (Draganov *et al.*, 2004). Another reason is that even though the same band-pass filter is applied to both gathers, the retrieved events seem to have lower frequency content due to a low-frequent bias in the non-flat amplitude spectrum. This might cause separate reflection events in the active data in some cases to appear as a single event in the retrieved results. Nevertheless, the retrieved result is very encouraging and we interpret the coherent events as retrieved reflections (primaries or multiples).

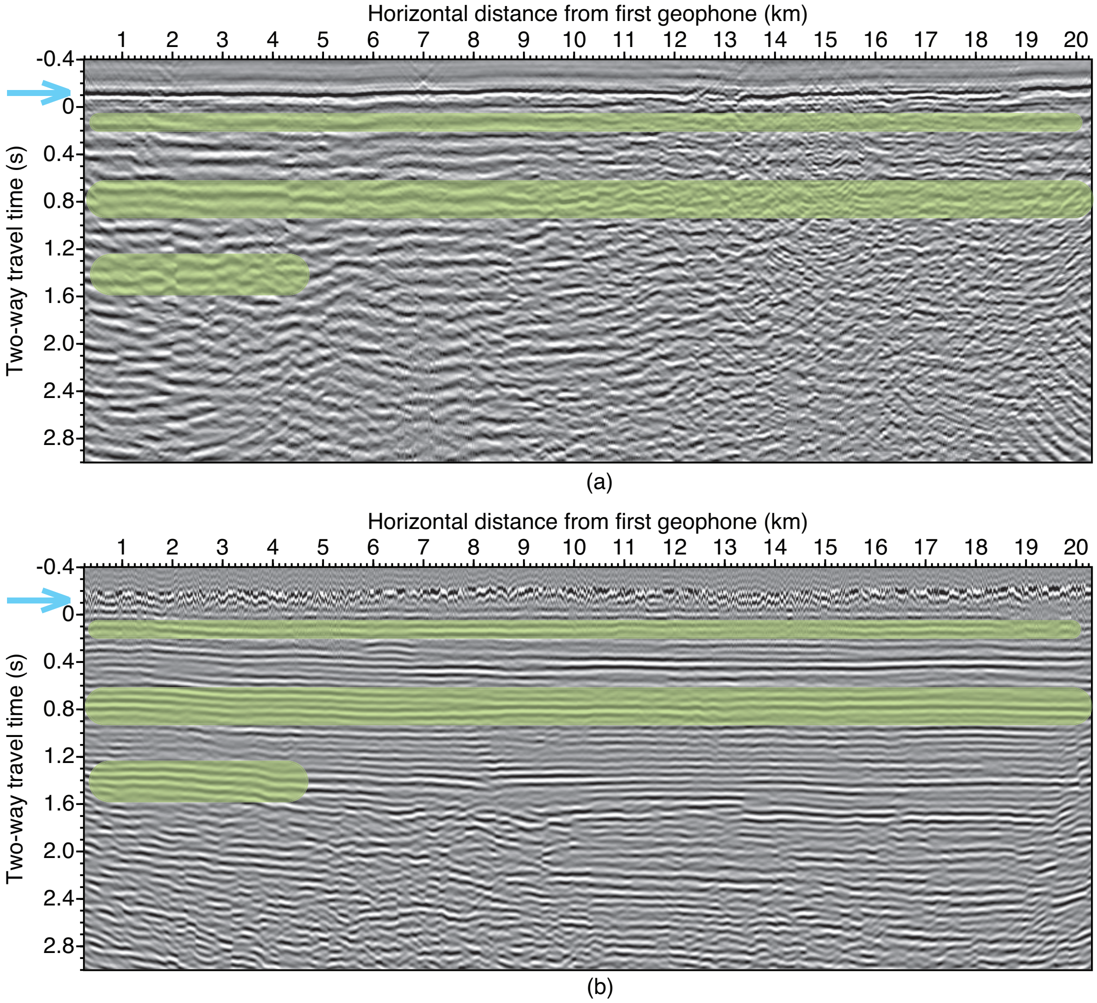


Figure 2: **(a)** Poststack time-migrated section obtained from the common-shot gathers as retrieved from the ambient-noise recordings. **(b)** Poststack time-migrated section obtained from the active data. The green areas highlight reflectors that coincide in time. The blue arrows indicate the position of the Earth's surface.

The above correlation procedure is repeated for all receiver positions, thus producing 412 retrieved common-shot gathers. We then apply a standard seismic processing flow (Yilmaz, 1999) to the retrieved gathers. The flow consists of statics correction, common-midpoint sorting, interactive velocity analysis (using velocity semblance and common-velocity stacks), normal-moveout correction, stacking, and finally phase-shift time migration. The retrieved time section is shown in Figure 2(a). In the left part of the section we see several coherent linear structures (highlighted in green in the figure). At locations relatively close to the traffic road around 14 km, it is not possible to identify unambiguously coherent structures. Despite our best efforts, there are still strong surface-wave remnants at these locations preventing the retrieval, and subsequently picking, of coherent reflections. At times beyond 1 s, the events in the stacked section loose their spatial coherence. Thus, as we would expect, due to the larger geometrical spreading of the body waves, it is more difficult to extract deeper reflections. We expect that a longer recording period could solve this problem. To be able to conclude whether the coherent linear structures are retrieved reflectors, we compare the retrieved time-migrated section with a post-stack time-migrated section from the active data (Figure 2(b)). To facilitate the comparison, the section from the active data has been band-pass filtered between 6 and 15 Hz (note that some filtering is visible above the Earth's surface. Comparing the two figures, we can see that the retrieved coherent linear structures coincide very well with reflectors in the active data.

Conclusions

We applied Seismic Interferometry to 11 hours of ambient seismic noise recorded in a desert region in North Africa. The results, retrieved from the cross-correlation, exhibited coherent hyperbolic events. Comparison of these events to data from an active reflection survey at the same location, confirmed that the retrieved events represent reflections. We further subjected the retrieved common-shot gathers to velocity analysis, normal-moveout correction, stacking, and phase-shift time migration. The resulting time section showed several coherent reflection events. Comparison of the retrieved migrated time section to a migrated time section obtained from the active survey, revealed that we have successfully retrieved several subsurface reflectors. The retrieval of reflection images from ambient noise may have large potential for seismic exploration and surveillance.

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References

Campillo, M., and Paul, A. [2003] Long-range correlations in the diffuse seismic coda. *Science* 299, 547–549.

Claerbout, J. F. [1968] Synthesis of a layered medium from its acoustic transmission response. *Geophysics* 33, 264–269.

Draganov, D., Wapenaar, K., and Thorbecke, J. [2004] Passive seismic imaging in the presence of white noise sources. *The Leading Edge* 23, 889–892.

Draganov, D., Wapenaar, K., Mulder, W., Singer, J., and Verdel, A. [2007] Retrieval of reflections from seismic background-noise measurements. *Geophysical Research Letters* 34, L04305, doi:10.1029/2006GL028735.

Schuster, G. T. [2009] *Seismic interferometry* Cambridge.

Shapiro, N. M., Campillo, M., Stehly, L., and Ritzwoller, M. H. [2005] High-resolution surface wave tomography from ambient seismic noise. *Science* 307, 1615–1618.

Wapenaar, K. [2004] Retrieving the electrodynamic green's function of an arbitrary inhomogeneous medium by cross-correlation. *Physical Review Letters* 93, 254301(4).

Wapenaar, K., Thorbecke, J., Draganov, D., and Fokkema, J. [2002] Theory of acoustic daylight imaging revisited. SEG.

Wapenaar, K., Draganov, D., and Robertsson, J. O. A. (eds). [2008] *Seismic interferometry: history and present status* Geophysics Reprint Series, vol. 26 Society of Exploration Geophysicists.

Yilmaz, O. [1999] *Seismic data processing*. Ninth edn. SEG, Tulsa, OK.