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Seismic Interferometry Applied to Passive Data

K. Wapenaar* (Delft University of Technology), D. Draganov (Delft University of Technology), W. Mulder (Shell International E&P Rijswijk), J. Singer (Shell International E&P Rijswijk) & A. Verdel (Shell International E&P Rijswijk)

SUMMARY

One of the applications of Seismic Interferometry (SI) is the reconstruction of the Earth's reflection response from the crosscorrelation of seismic background noise recorded at the surface. In recent years, several authors have derived the relations that govern this process. The quality of the reconstruction has been extensively examined with numerical modeling results.

We applied SI to background-noise field data recorded in a desert area. The reconstructed results show several coherent events which align well with reflections from an active survey along the same line.

Introduction

The term 'seismic interferometry' refers to the principle of generating new seismic responses by crosscorrelating seismic observations at different receiver locations. In 1968 Claerbout derived a remarkable relation between the transmission and reflection responses of a horizontally layered lossless medium, bounded by a free surface (Claerbout, 1968). He showed that the autocorrelation of the transmission response is equal to the reflection response plus its time-reversed version (plus an impulse at time zero). This implies that when one measures the response of a plane wave source in the subsurface by a geophone at the free surface, the reflection response is obtained simply by taking the causal part of the autocorrelation of the observed response. Primary as well as multiple reflections are recovered correctly by this procedure. The source wavelet in the recovered reflection response is equal to the autocorrelation of the source signal in the subsurface. Hence, if one would measure the response of a band-limited white-noise source in the subsurface, the autocorrelation would give the impulsive reflection response, convolved with a band-limited delta function. This is quite fascinating, since it shows that noise observed at the surface can be turned into signal with information about the subsurface. Later Claerbout conjectured that his relation could be generalized for offset measurements in 3-D inhomogeneous media, i.e., that by crosscorrelating noise traces recorded at two locations on the surface, one can construct the wavefield that would be recorded at one of the locations as if there were a source at the other. Since its conception, several attempts have been made to make this idea work on real data, some more successful than others (Scherbaum, 1987; Cole, 1995; Daneshvar et al., 1995; Rickett and Claerbout, 1999). Curiously, the first convincing results have been obtained by solar seismologists (Duvall et al., 1993).
In the exploration geophysics community, the research on retrieving information from crosscorrelations got new momentum after a sabbatical stay of Jerry Schuster at the Stanford Exploration Project in 2000. He applied the correlation method not only to passive data but also to exploration seismic data with man-made sources. Schuster introduced the concept of interferometric imaging, which involves an integration of crosscorrelation and migration. He supported his interferometric imaging method by an elegant theory based on stationary phase analysis (Schuster, 2001). Schuster's coworkers at the University of Utah, notably Jianhua Yu and Jiaming Sheng, successfully applied his method to various types of data, including shot records, VSP data and drillbit data. In the meantime, the Delft Applied Geophysics group developed a theory for seismic interferometry, based on seismic reciprocity, which formally generalizes Claerbout's relation between transmission and reflection responses to acoustic and elastic 3-D inhomogeneous anisotropic lossless media (Wapenaar et al., 2002). Draganov et al. (2003) confirmed this theory with numerically modelled data in laterally varying media. In this paper we present results of applying seismic interferometry to real data.

Field experiment description

In 2005, Shell carried out a small field experiment to test the applicability of seismic interferometry with seismic background noise for the reconstruction of the reflection response. The experimental set-up consisted of 17 standard industry 3-component geophones arranged in a single line. The geophone spacing was 50 m and the time-sampling rate was 4 ms. The array was planted in a desert area. The particular site was chosen so that there would be an active seismic survey available along the line to allow for verification of the reconstructed results and that the cultural noise was minimal during the recording of the background noise. Standard exploration equipment was used, which allowed for a maximum record length of 70 s. The background noise recording was then interrupted for 30 s to store the already acquired record. To be able to reconstruct the reflection response of a medium from the crosscorrelation of noise, one needs time series at least of the order of hours. For this reason, 524 records of 70-seconds were acquired, amounting to about 10 hours of seismic background-noise data.

Reconstruction of the reflection response

By crosscorrelating the first trace at x=0 (called the master trace) with all other traces we reconstruct a common-shot gather as if from a source at x=0. Inspection of the frequency spectrum of the background-noise panels showed that the useful information is mainly below 12 Hz. For this reason, the reconstructed results were band-pass filtered between 2 and 10 Hz. Figure 1 shows the intermediate results from building the final reconstructed common-shot gather by using two hours of noise data (Figure 1a), 4 hours (1b), 6 hours (1c), 8 hours (1d) and, finally, by using the full 10 hours of the recorded noise data (Figure 1e). The panels were clipped to emphasize the events at later times. One can appreciate how the increase of the recording times leads to more subsurface information and increases the signal-to-noise ratio. Due to the short array spread and the low frequencies and due to the fact that the geology in the area is composed of nearly horizontal layers, the reflection events below 1.5 s should appear nearly horizontal.

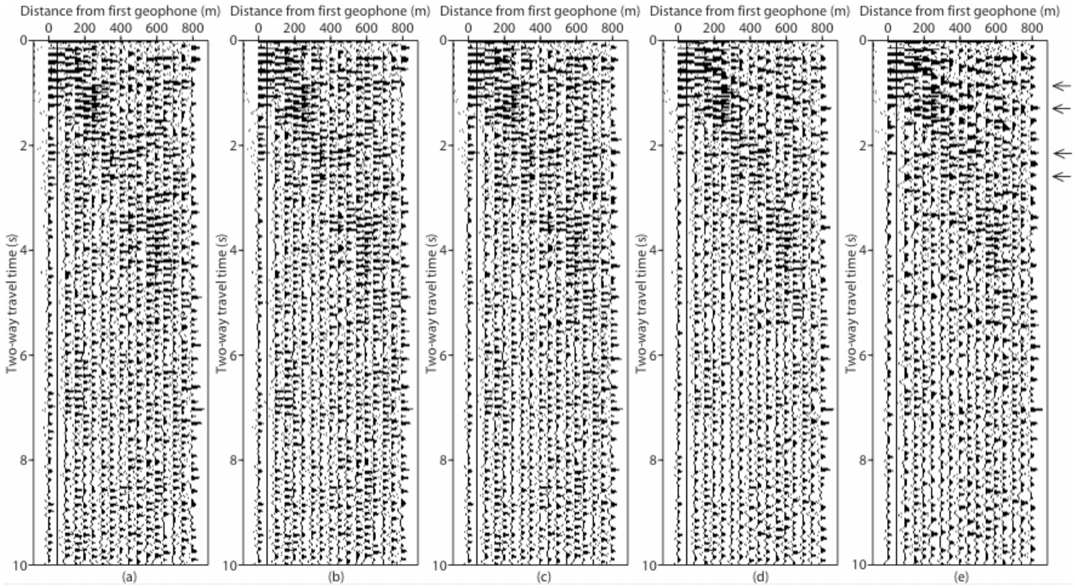

Figure 1: Reconstructed common-shot gather as if from a source at x=0, obtained by crosscorrelating the noise trace at x=0 with all other traces, using 2, 4, 6, 8 and 10 hours of noise, respectively.

Figures 1a-1e show actually only the causal part of the two-sided crosscorrelation. In theory the crosscorrelation is symmetric in time, in practice it is not. Figure 2a shows the first 10 s of the causal part of the crosscorrelation result, Figure 2b the first 10 s of the time-reversed anti-causal part and Figure 2c shows the sum of Figures 2a and 2b. One can clearly see that the causal and the anti-causal part are not the same. That is why one should look at their sum, which gives a more complete reconstruction.
By changing the position of the master trace along the receiver array we reconstructed common-shot gathers with simulated sources positions at x = 0, 100, 150, ..., 800 m (note that the second geophone was dead). These reconstructed shot records are not shown but will be used in the following experiments.

In the experiments above we have made no assumption about the subsurface (except that it is assumed lossless). In the next experiment we make use of the fact that the subsurface is nearly horizontally layered. This helps us to improve the signal-to-noise ratio. We sorted the reconstructed common-shot gathers into common-offset gathers. The traces in the individual offset gathers were summed together, the resulting trace was divided by the number of summed traces and assigned to the corresponding offset. This operation should bring forward any coherent events that were present in the reconstructed results. The result of this common-

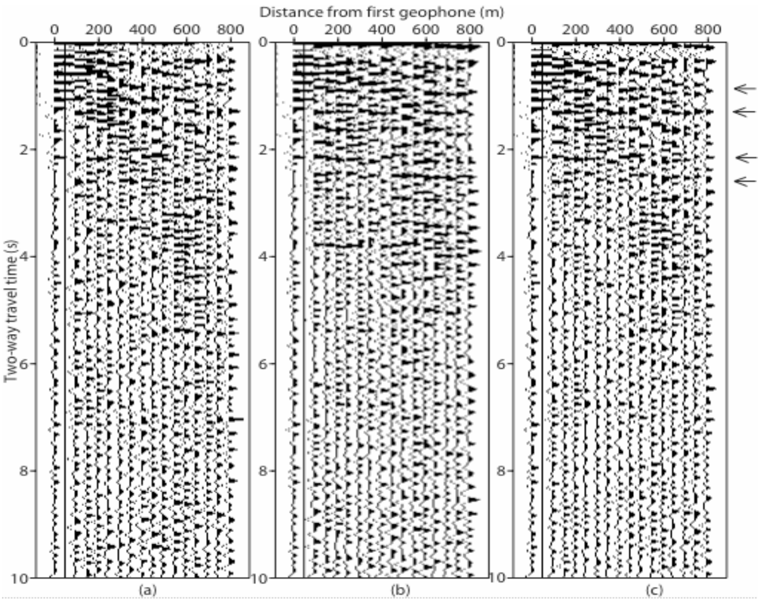

Figure 2: (a) Causal part of the crosscorrelation result. (b) Time-reversed anti-causal part of the crosscorrelation result. (c) Result of the summation of (a) and (b).

offset stack operation is a reconstructed common shot gather with improved signal-to-noise ratio, see Figure 3a. Automatic Gain Control (AGC) was applied to bring forward the late arrivals. For comparison, Figure 3e shows a common shot gather obtained by finite-difference elastic forward modeling, for which we used a simplified 1D model based on the results from an active survey. This panel is included to show the shape of the expected coherent arrivals (and in this way to help the interpretation of Figure 3a) and should not be used for travel-time comparison. Another way of improving the signal-to-noise ratio, without the need of assuming the medium is horizontally layered, is by applying a brute stack of the traces in each individual reconstructed common-shot gather. The resulting trace is assigned at the position of the simulated shot position of the corresponding shot gather. This operation is equivalent to simulating a physical plane-wave experiment, where the receiver array would emit a plane wave and record its response. The result of this approach is that (nearly) horizontal coherent events will be amplified. At the same time, random noise, inclined coherent events and reflections with moveout will be suppressed. The result of this operation is shown in Figure 3b. Note that AGC was used to boost the later arrivals. One can see clear presence of several coherent horizontal events, which can be reconstructed reflections. These events are pointed out with arrows. The first two of the horizontal events were not that clearly visible on the common-offset stack panel (Figure 3a). We compare the results with a Post-Stack Time Migrated (PSTM) section (Figures 3c,d) from an active reflection survey along the same line of geophones. The active survey PSTM data was low-pass filtered till 20 Hz as it did not contain information below 8 Hz. Despite the difference in frequency content, the comparison of Figure 3b with 3c shows that the four coherent horizontal events pointed out with the arrows can potentially be reconstructed reflections. The active reflection data was 6 s long and therefore that did not allow a comparison of later arrivals.

Conclusions

We applied seismic interferometry to ten hours of passively acquired seismic background-noise data. The crosscorrelation produced coherent events in the reconstructed shot gathers. The crosscorrelation results were band-pass filtered between 2 and 10 Hz. We applied two methods to improve the signal-to-noise ratio. The results were compared with a post-stack time migrated section from an active reflection survey. The reconstructed horizontal coherent events appear to align very well with imaged reflectors from the active survey.

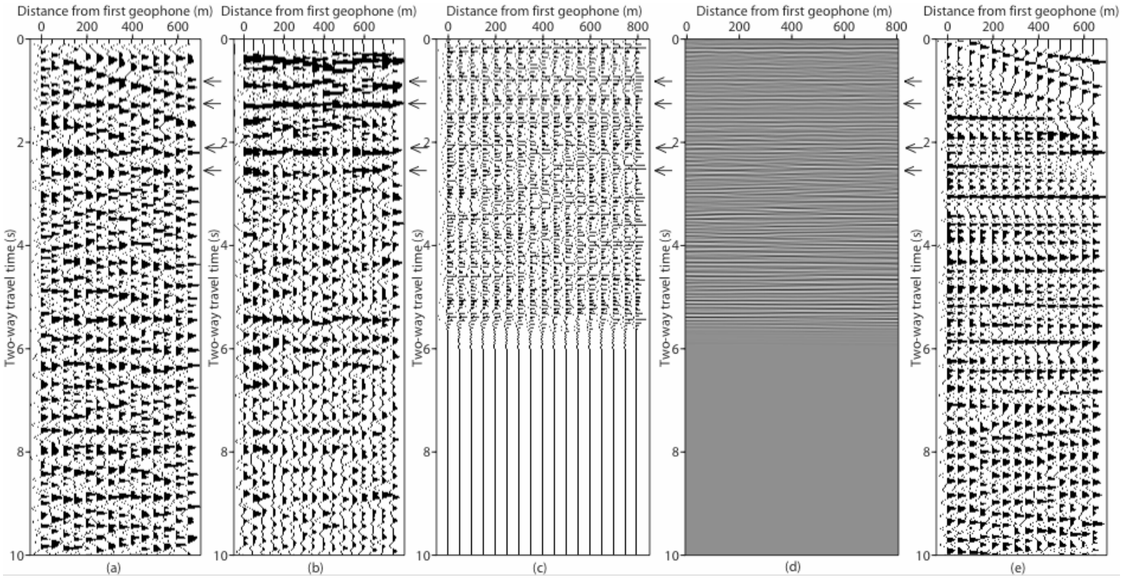

Figure 3: (a) Reconstructed common-shot gather with improved signal-to-noise ratio (see text for explanation). (b) Plane-wave response (see text). (c) Time migration result of active reflection data. (d) Idem. (e) Finite-difference modeling result.

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