Stanford Exploration Project, Report 65, January 13, 1998, pages 175–190

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Comparison of different approaches to processing ambient noise data

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keywords: *noise, sources, processing, velocity*

ABSTRACT

Various methods of processing ambient noise data and teleseismic coda waves, recorded by seismic arrays, have been developed by different groups. The main goal of these investigations is to locate endogenous sources of microseisms beneath the array (in the ambient noise case) or to detect scattering (in both cases). In the simplest processing scheme, semblance is used to measure the coherent energy exhibiting hyperbolic moveout arriving from sources (primary sources or scatterers) in the medium. The processing reveals some possible sources at depth, but the results are strongly influenced by surface sources. To eliminate the influence of these sources, a least-squares method in the frequency domain has been applied, but the method is hampered by the problem of estimating a source signal, which is required by the algorithm.

INTRODUCTION

In recent years, several studies have sought to obtain additional information from the parts of seismic records which are treated as obstacles in traditional studies. Examples of such data are records of microseismic noise and teleseismic coda waves. In the case of coda waves it is possible to detect irregularities in the structure of the Earth's crust, which act as sources and scatter teleseismic waves. Study of microseisms may also yield information about processes in the Earth's crust. Microseismic noise can be due to different sources, such as zones of anomalous temperature or pressure in oil and natural gas reservoirs (particularly during industrial exploitation) or active seismic faults. Seismic noise research can be applied to the monitoring of such processes.

In the department of experimental seismology at the Institute of Physics of the Earth (Moscow, USSR), methods for processing noise and noise-like data are being developed (Nikolaev and Troitskiy, 1987). One algorithm constructs a 3-D grid in the subsurface, and then computes the semblance coefficient for energy arriving from a source at each point in the grid. Using this method, records of coda waves and

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microseismic noise, both recorded by the NORSAR array in Norway, were processed. Also, in 1988, the same group conducted an experiment in Iceland to measure microseisms using a sparse 2-D array of geophones. The same semblance method was used to locate subsurface sources. The results are reviewed in this paper.

One of the problems inherent in such work is the presence of conflicting signals arriving from many noise sources. In particular, surface noise sources are relatively strong compared to endogenous sources or scattered energy. We discuss a frequency-domain least-squares method that can suppress the signal generated by strong surface source and improve the detection of weak subsurface sources.

At SEP, an experiment was conducted to record ambient noise (Nichols et al, 1989; Cole, 1989) using a compact, more densely-sampled array, with the goal of observing scattering of ambient noise energy and of energy from quarry blasts. Stacking-based methods were used to first examine the plane wavefield incident on the array, and then to look for scattering in a manner similar to that used in the Russian experiments. In this paper we use some of the techniques developed at SEP to supplement our review of the Russian work and the processing of the microseismic dataset from Iceland.

Semblance processing of the data

As mentioned above, a semblance method is used to look for sources. First we create a 3-D grid of points in the subsurface. Then for each point in the grid, knowing the velocity model, we compute the moveout trajectory that energy originating from a source at that point would follow. The semblance is computed along that trajectory, and averaged over time.

A simple model of the seismic record is assumed:

$$S_i(t) = \sum_{k=1}^{N} x_k(t - t_{ki}) + n_i(t).$$

Here x_k is the signal generated by source k, t_{ki} is the time delay, determined by velocity model and the positions of the source k and geophone i, and n_i is spatially uncorrelated noise.

An additional assumption is that signals from different sources are mutually uncorrelated and that signals from any source are well correlated from geophone to geophone.

This model is obviously too simplistic to give an accurate description of the real situation, but the idea is that if there is a powerful enough source beneath the array, it will be possible to detect it using this model.

Assuming that the velocity model of the area is known, a simple coherency measure, the semblance coefficient, can be computed:

$$Sem(x, y, z) = \frac{\sum_t \left(\sum_i S_i(t + t_i)\right)^2}{M \sum_t \sum_i S_i^2(t + t_i)},$$

Here x, y, and z are the coordinates of a point in the medium, t_i is the travel time from that point to geophone i, and M is the number of channels.

The semblance coefficient is convenient because of the following property: If seismograms are absolutely uncorrelated, then it equals $1/M$, and in the case of good correlation the semblance tends toward 1. That means that if there is a source of seismic energy at some particular point in the medium, we can expect to detect a large semblance value at that point.

We will apply this method to microseismic noise data from the Iceland experiment. But first we will describe the experiment and use some software developed at SEP to analyze the ambient wavefield.

A MICROSEISMIC DATA EXAMPLE

In 1988 the department of experimental seismology at the Institute of Physics of the Earth in Moscow conducted a seismic experiment in Iceland, recording microseismic noise with a 2-D array of geophones. The main purpose of the experiment was to attempt to locate endogenous sources of microseisms beneath the array. Earlier electrical studies had shown that there were possibly hydrotherms at depths around 1 km in the vicinity of the experiment site. It was speculated that these hydrotherms might be good sources of microseismic activity, so an experiment was designed to attempt to locate them using ambient noise data. The velocity structure in the area, determined by conventional seismic surveys, showed the subsurface consisted primarily of horizontal layers.

Conventional seismic recording equipment was used to record the background noise, using a two-dimensional array of 24 channels. The array geometry is shown in Figure **??**. A 2 ms sampling rate was used, and the length of each record was one minute.

Preprocessing and data processing were done in Moscow by Shubik and Kisilevitch. The semblance processing has been repeated at Stanford, using SEP software to plot the results.

Raw traces from one record are shown in Figure 1. Some traces are contaminated by strong noise bursts which are not correlated between channels. Since we expect signals from sources at depth to be well correlated, these strong bursts were removed by applying a time-varying automatic gain. The data were also lowpass filtered with a cutoff frequency of 12 Hz.

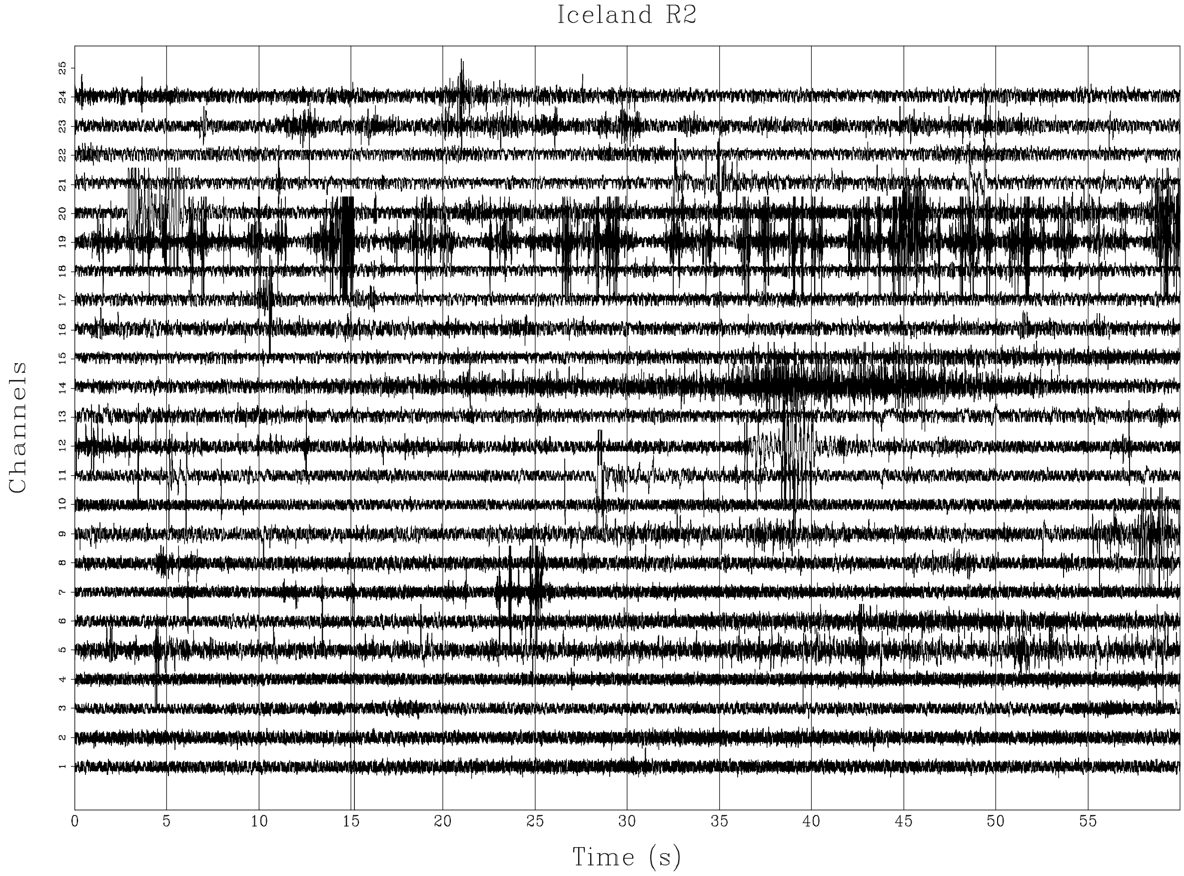

Figure 1: Plot of the raw traces for one record. The strong noise bursts are localized in space and therefore due to some local noise source that is not of interest. A time-varying gain was used to suppress these bursts. leo-trace [NR]

Stacking Analysis

We would first like to verify that there is a substantial amount of coherent energy in the data. It is difficult to inspect the data visually in 3-D for coherency. Lin Zhang at SEP found a useful way to get a first look at the coherent energy present in the data. He partially stacks the array data along four different profiles. This procedure yields four stacks which can be placed side by side, to give an initial view of the energy and moveouts present in the data. Figure **??** shows the four directions along which the data were partially stacked, the "inline" and "crossline" directions of the array, and the two diagonals. Figure **??** shows the four stacks produced for a four second portion of one record. While the signal to noise ratio is not large, it is clear that there is some coherent energy present in the data; several different moveouts can be seen on close inspection.

Beam steering

Having seen some coherent energy in the data, we now would like to determine precisely where it is coming from. Beam steering is a process that determines the plane wavefield incident on the array as a function of arrival direction. Beam steering is equivalent to a 3-D slant stack. We stack the data (or compute semblance) along many different planar trajectories, and display the results, either as a function of time or averaged over time.

Figure **??** illustrates one way in which the results of beam steering analysis can be presented. In this figure, the semblance value for plane wave energy is displayed as a function of the apparent slowness of the plane wave and the azimuth direction (or equivalently, as in slant stacking, as a function of the ray parameters p_x and p_y). A vertically propagating plane wave has zero apparent slowness, thus the center of the plot gives the semblance value for vertical incidence. The extreme edge of the plot corresponds to an apparent velocity of 2 kilometers per second. If the medium velocity at the surface is also two kilometers per second, then this corresponds to energy propagating horizontally. Thus in this one plot we get an idea of the plane wavefield incident on the array in all directions.

Figure 2 shows semblance values for plane waves incident on the array for two of the records from the Iceland dataset. Each record in the dataset was 60 seconds long. We compute semblance as a function of azimuth, apparent velocity, and time, and then average semblance over the time axis to produce a composite picture for the entire record. There is clearly agreement between the two records. Energy arrives from the upper left at an apparent velocity of 2 kilometers per second. Since we know that the near-surface velocity is about 2 kilometers per second, this energy is most likely propagating horizontally from a surface source (most likely a river known to lie in this direction). More interesting is the energy that arrives at higher velocities. It could represent endogenous sources within the earth or scatterers.

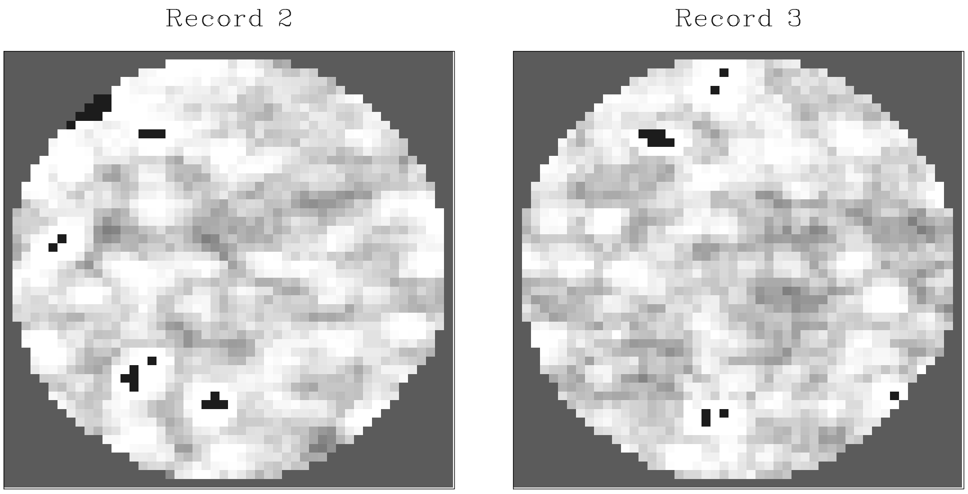

Figure 2: Semblance measure of the plane wavefield incident on the array for two different records of the Iceland dataset. Semblance has been averaged over time to produce a single image for each record. White denotes a large semblance coefficient. The largest semblance values have been clipped and are shown in black. There is considerable agreement between the two. The outer edge of the circle corresponds to an apparent velocity of 2 kilometers per second. Energy arriving at this apparent velocity is most likely from a source on the surface. A river located in the direction to the upper left is suspected to be a strong surface source. leo-beam1 [NR]

Crosscorrelation

Crosscorrelation can be used to enhance a signal embedded in noise. For instance, if we had a source waveform for the surface source that we see in Figure 2, we could crosscorrelate our recorded traces with this wavelet. Energy from this surface source would be enhanced after crosscorrelation at the expense of other signals.

While we suspect the surface source in Figure 2 to be a nearby river, we do not have a source waveform to use in crosscorrelation. However, we might suppose that traces near the source are strongly influenced by it and use one of these traces as the source waveform in crosscorrelation. Figure 3 shows the result of crosscorrelating the raw data from Figure 1 with a single channel from the array. Moveout of a signal (the surface source) is readily apparent in the crosscorrelated result.

An interesting point to note is that crosscorrelation preserves the moveout in the original data. Thus we can beam steer the crosscorrelated output just as we would the raw data. And since crosscorrelation compresses the data, moveouts are located in a small zone centered on the zero lag, and beam steering can be less expensive than when long time records must be stacked. The improvement in quality of Figure 3 over the raw data in Figure 1 suggests that beam steering will be able to define the source much more accurately after crosscorrelation.

The result of beam steering the crosscorrelated data is shown in Figure 4. Because

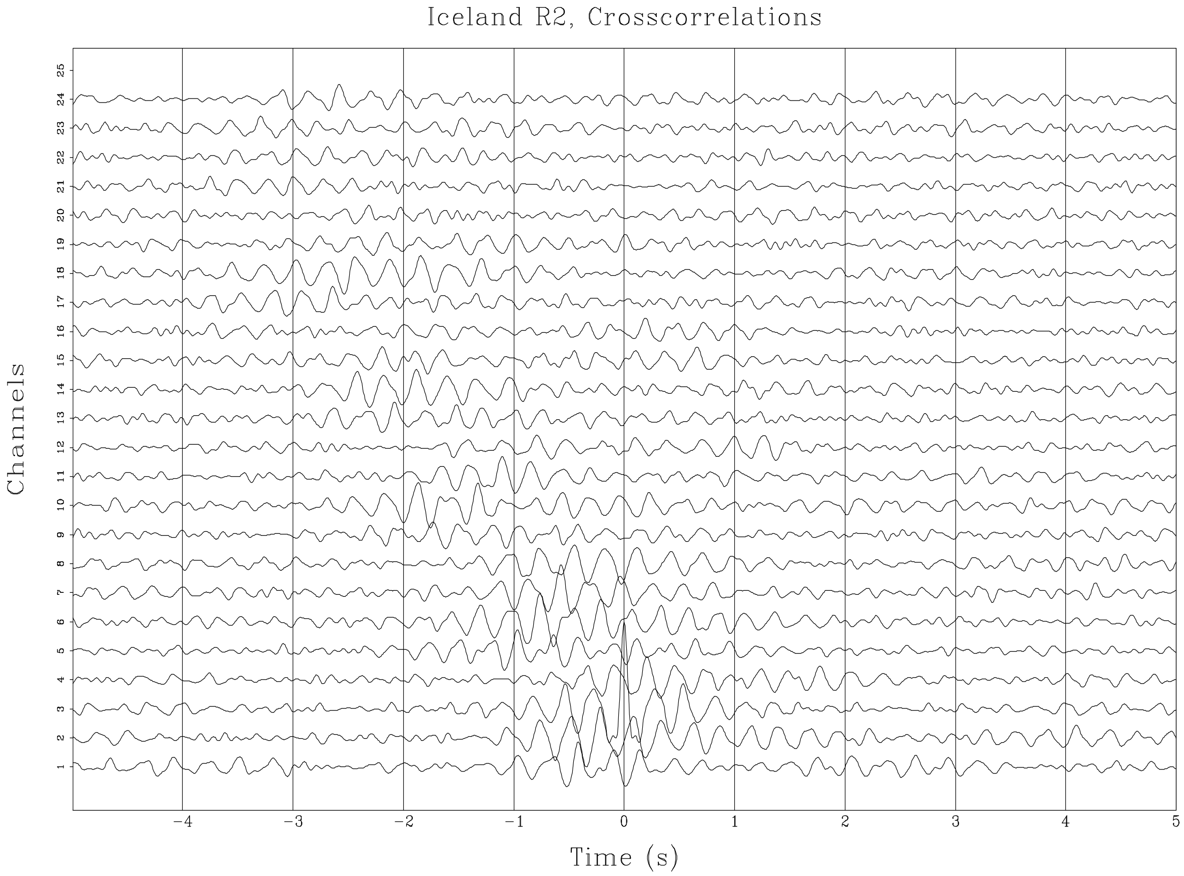

Figure 3: The raw data from Figure 1 have been crosscorrelated with a single channel to enhance the strong surface noise source. Crosscorrelation preserves the moveout present in the raw data. leo-ju1 [NR]

it dominated the near trace that we used in crosscorrelation, the nearby surface source is the dominant feature in the beam steered result. In a later section of this paper, we will use the improved image of the surface source provided by crosscorrelation to suppress this source and enhance sources at depth.

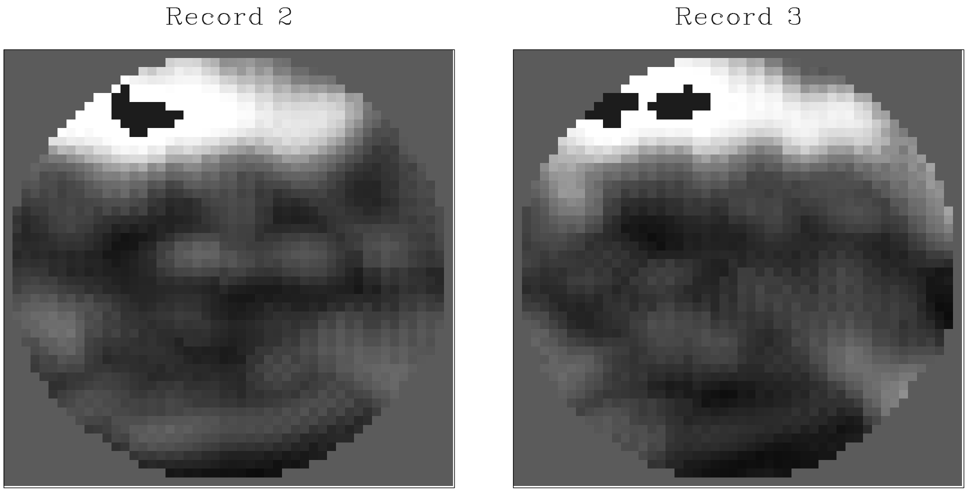

Figure 4: Data from the array have been crosscorrelated with a single trace and the nearby surface source has been enhanced. leo-beam2 [NR]

A single trace selected from the array may not be the best estimate we could make of the source waveform. From Figure 4, we know very well the parameters that characterize the moveout trajectory of energy from the nearby surface source. We can compute this trajectory, stack the data along it, and use this stacked trace as the source signal in crosscorrelation. After doing so, we have beam steered the crosscorrelated data. The result is shown in Figure 5. Using the stacked trace has improved the correlation and made the surface source even more dominant in the beam steered result. This improved picture of the source will aid us when we try to suppress it.

DETECTION AND LOCATION OF SOURCES

Locating weak endogenous sources against a background of powerful and well-correlated surface noise is a difficult problem. Unfortunately, since most data is recorded on the surface, we must learn how to deal with strong surface noise sources.

If we can estimate the signal generated by a particular source, then we can eliminate the influence of that source from the data using a least-squares technique to be discussed here. An important step, however, will be determining the source signal to be used in the suppression algorithm.

To test our method of surface noise suppression, we created a synthetic dataset with a single source at a depth of 1000 meters, and added uncorrelated noise with

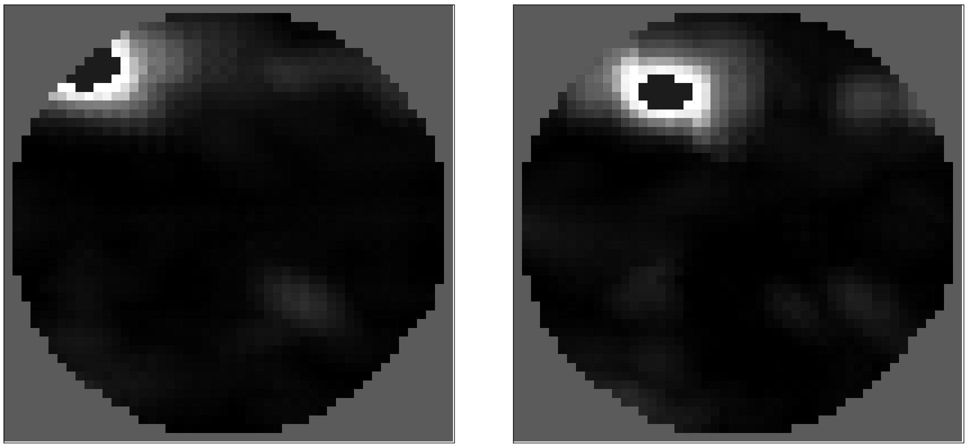

Figure 5: Data from the array have been crosscorrelated with a trace formed by stacking the array data along the moveout trajectory for energy arriving from the nearby surface source. This improved source estimate has improved the correlation and reduced the influence of other sources on the beam steered result. leo-beam3 [NR]

a signal to noise ratio of 1:1. Figure 6 shows the semblance computed for constant-depth slices of the 3-D volume. The dimensions of each panel correspond to the dimensions of the array. The maximum semblance is obtained, as expected, on the panel corresponding to a depth of 1000 meters.

Next we added a strong surface noise source at a distance of 3 km from the array, with the power of the surface source 100 times the power of the buried source. Figure 7 shows semblance results for the two-source case. The strong surface source has effectively hidden the weaker source at depth.

Given an estimate of the signal of the surface source, we can suppress it using the following formula: (Jenkins, 1968):

$$X_{ir}(f) = X_i(f) - \frac{\overline{X_{0i}(f)}}{\overline{X_{00}(f)}} X_0(f),$$

where $X_i(f)$, $X_0(f)$, $X_{ir}(f)$ are the Fourier transforms of the ith trace, the reference trace (the source signal) and the residual trace, respectively. $\overline{X_{0i}(f)}$ is a smoothed estimate of the cross-spectrum between the reference trace and trace i, and $\overline{X_{00}(f)}$ is the power spectrum of the reference trace.

What are we to use for the source signal? As a first guess, we took the data from one recorded channel and used it as the source signal. Figure 8 shows the semblance result computed after applying the noise suppression technique. The influence of the surface source has been removed almost completely, and it is now possible to identify the deep source.

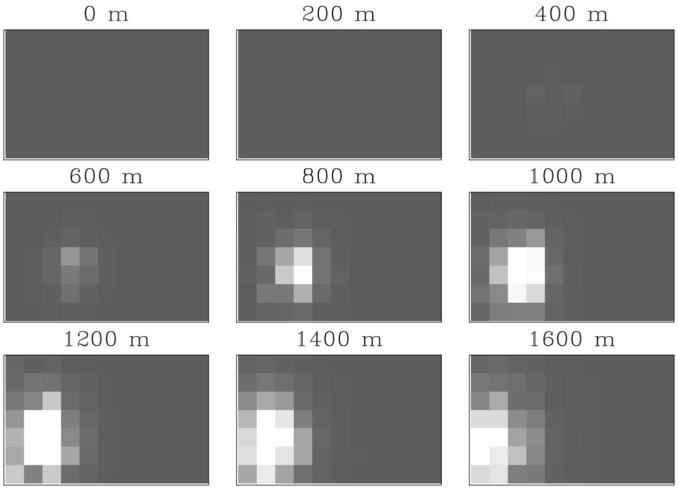

Figure 6: Semblance computed from synthetic data with one source located at a depth of 1000 meters. leo-sesi1 [NR]

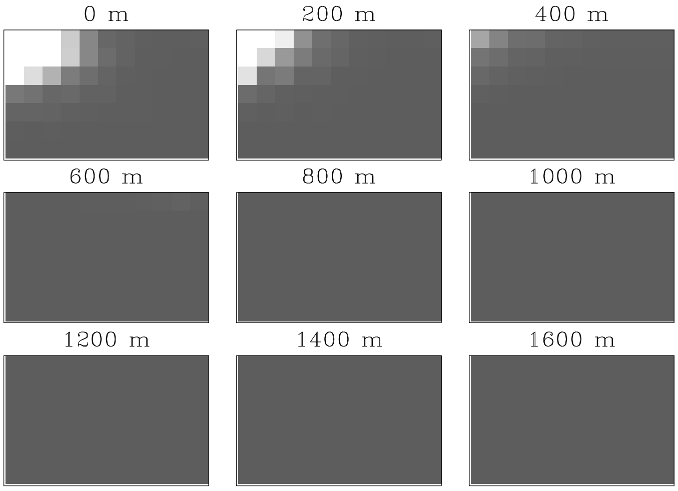

Figure 7: Semblance from synthetic data with one source located at a depth of 1000 meters and a surface source whose amplitude is ten times larger. The weaker source at depth is effectively masked by the strong surface source. leo-sem2 [NR]

Application to microseismic data

We now wish to apply the surface noise suppression technique to real microseismic data from the Iceland experiment. Figures 9 and 12 show the result of performing the semblance computation for two records from the Iceland data (the same two records as shown in the beam steering examples earlier). The maximum semblance values at shallow depths correspond to a known surface source, a river situated 1.5 to 2 kilometers from the array.

To suppress the signal from the surface source and look for sources at depth, we applied the surface noise suppression method described above. A single recorded trace was used as the first estimate of the source signal. Figures 10 and 13 shows the results of the semblance computation after surface noise source suppression. It is clear that the effect of the surface noise source has been reduced somewhat on both records.

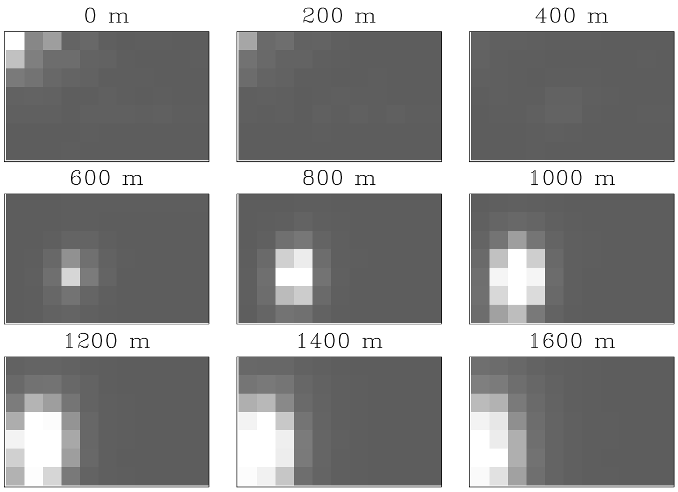

Figure 8: Semblance from synthetic data after suppression of the strong surface noise source. It is now possible to see the source at depth once again. leo-sr10 [NR]

We theorized that we could do a better job of suppressing the surface noise source if we came up with a better estimate of the source signal. From Figure 2, we can measure the apparent velocity and azimuth that characterize arrivals from the surface source. Using these parameters, we can compute the moveout trajectory of energy coming from that source, and stack the data along that trajectory. This stacked trace should be a better estimate of the source signal than a single trace, because only the energy from the surface source will stack constructively. Figures 10 and 14 show the semblance after suppressing the surface source, using the stacked trace as the source signal. The two source signal estimates give rather similar results. We think that this similarity shows that the surface source is much stronger than all other sources, since the benefits derived from stacking were not very large.

Suppression of the surface source appears to have revealed a source at a depth of around 1 kilometer for record R3, but not for record R2. Note the similarity between the result for R3 and the results for the synthetic dataset presented earlier. If we believe the results of R3, why is the picture so different for R2? Perhaps a better source estimation method would improve the results for R2, or perhaps the source was more active during the recording of record R3.

Beam steering after surface noise suppression

Figure 15 shows the result of beam steering the data after the first pass of surface noise suppression, where a single recorded trace was used as the source waveform. Figure 16 shows the result of beam steering after the second pass of surface noise suppression, where the source waveform was computed by stacking along the surface noise source's moveout trajectory. Note the dark areas in the upper left of the plots in Figure 16; these are not large semblance values which have been clipped, but the small semblance values that remain after surface noise suppression has done a very good job.

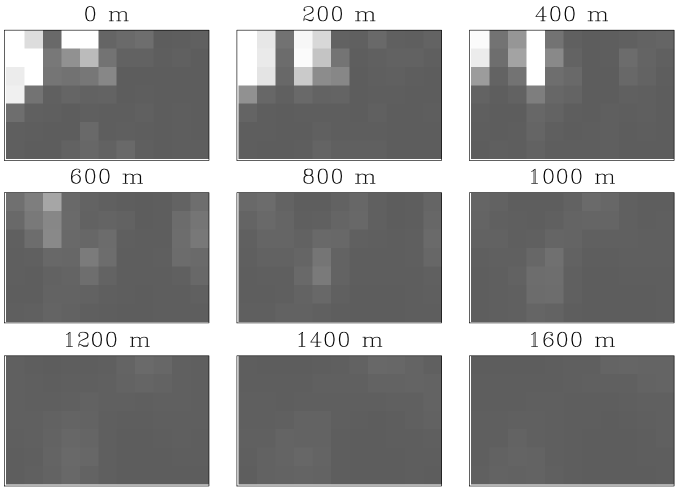

Figure 9: Semblance for microseismic data, record R2. leo-semis2 [NR]

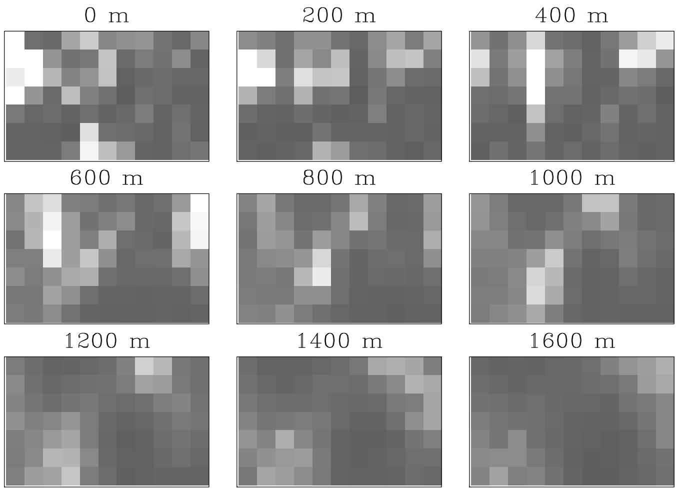

Figure 10: Semblance for microseismic data, record R2, after surface noise suppression. Data from one channel were used as the source signal in the noise suppression algorithm. leo-is2r [NR]

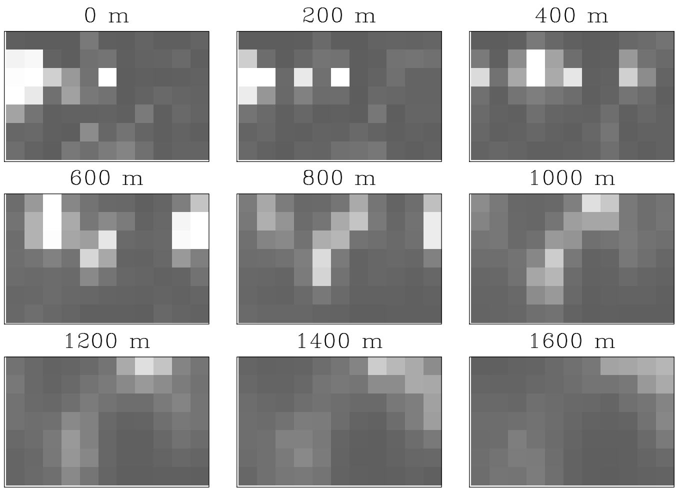

Figure 11: Semblance for microseismic data, record R2, after surface noise suppression. Here we computed the source signal for the noise suppression algorithm by stacking the data along the moveout trajectory appropriate for the nearby surface source. leo-se2ra [NR]

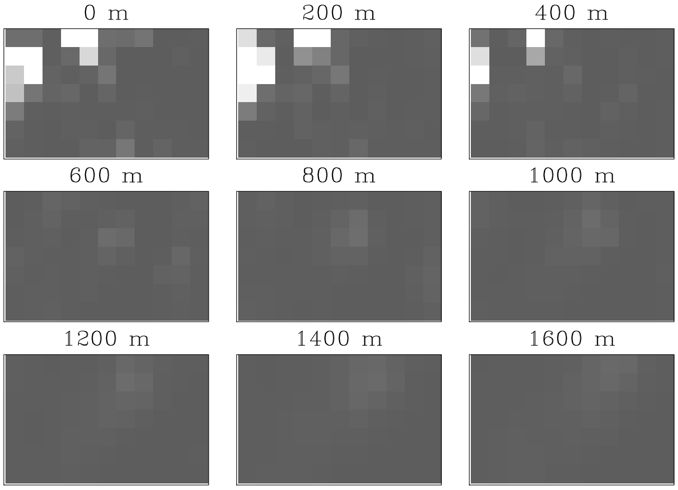

Figure 12: Semblance for microseismic data, record R3 leo-semis3 [NR]

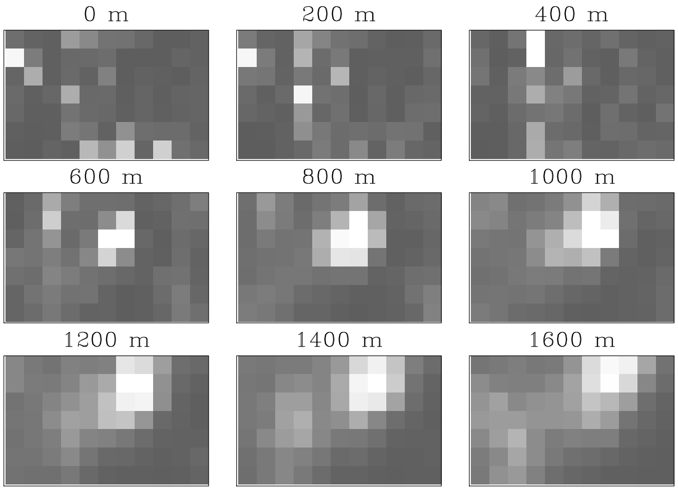

Figure 13: Semblance for microseismic data, record R3, after surface noise suppression. Data from one channel were used as the source signal in the noise suppression algorithm. leo-semis3R [NR]

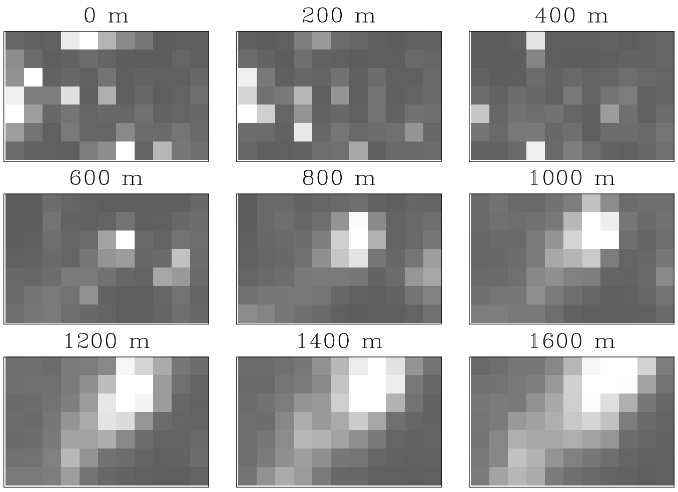

Figure 14: Semblance for microseismic data, record R3, after surface noise suppression. Here we computed the source signal for the noise suppression algorithm by stacking the data along the moveout trajectory appropriate for the nearby surface source. leo-se3es [NR]

It is interesting to note that beam steering suggests that the second application of surface noise suppression was much more effective, while the semblance results for the two applications were comparable. Perhaps an improved method of estimating the source signal would improve both results.

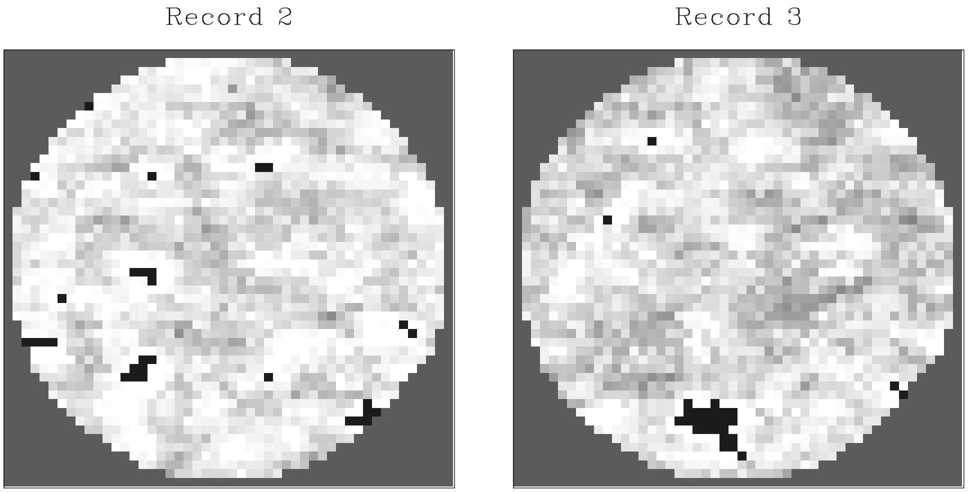

Figure 15: Beam steering after the first pass of surface noise suppression. The algorithm has done a reasonably good job of suppressing the surface noise source in the upper left. Other plane waves at higher apparent velocities are relatively enhanced by the suppression of the surface source. leo-beam4 [NR]

CONCLUSIONS

Location of sources of microseismic energy or scatterers at depth is a difficult process due to the presence of strong sources of noise on the surface. We presented a method of suppressing surface noise sources that seems to have been somewhat successful. An important step in the processing is the estimation of the signal of the surface noise source. We have found it helpful to use beam steering to determine the moveout trajectory of energy from the surface source, and then stack the data along this trajectory to obtain a robust signal estimate. Perhaps better methods of estimating the signal of the source will lead to better noise suppression results.

Obviously, the results obtained from such data depend greatly on the quality of the data collection (including the time and place at which the data are recorded). Borehole data would probably yield better results, because it is less sensitive to surface noise sources.

ACKNOWLEDGMENTS

We wish to thank the members of the department of experimental seismology at the Institute of Physics of the Earth, Academy of Sciences of USSR, who collected the

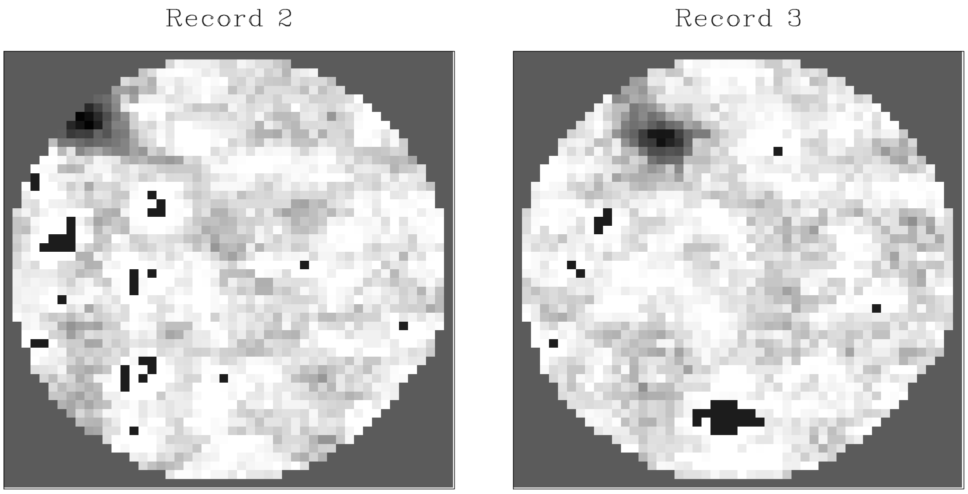

Figure 16: Beam steering after the second pass of surface noise suppression, where the source waveform was created by stacking along the moveout trajectory of the surface source. Now the algorithm has done a much better job of suppressing the source, at least in Record 3. The dark area near the upper left is not large amplitudes that have been clipped; it is the small amplitudes that remain after the surface source has been removed very well. leo-beam5 [NR]

Iceland data and made it available for our work.

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