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Scattering analysis of passive seismic data

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ABSTRACT

Blasts set off in a quarry 15 km from the SEP passive experiment site are easily detected, even if they are quite small, using beam steering. These blasts have provided a signal with which various processing techniques can be evaluated before being applied to ambient noise data. One such technique is imaging by looking for evidence of diffraction off near-surface structures. This yields a picture that is fairly consistent but dominated by plane-wave energy arriving in the same direction as scattered waves. One of the most surprising results of the experiment is the observation of many weak near-vertically incident events during nighttime recording. While their origin has yet to be explained, these events are not due to electrical interference.

INTRODUCTION

In September of 1988 the SEP conducted a passive seismic experiment on Stanford land, setting out 4056 geophones in 24-geophone groups, giving 169 independent recorded channels. The survey area was a square roughly 500 meters on a side. Our goal was to use industrial recording techniques to record ambient seismic noise and use it to image the subsurface.

In SEP–60, the results of some initial processing of the data were presented. The results were not very encouraging, but since then processing tools have evolved and I have made some significant gains. In this report, I will discuss three topics I've been working on. First, the USGS set off several blasts varying in size in a quarry about 15 km away from our experiment, timed so that we could record them. Two of the three blasts were so small that they are not observable on single geophone records at our site. But beam steering or slant-stacking of the data sees these blasts quite well. There is evidence in the coda of at least one blast of multipath effects, which deserve closer study.

Second, we have observed a large number (one every few seconds during nighttime recording) of weak, near-vertically incident events. While we cannot explain their

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origin, it will be shown here that while they are nearly vertically incident (as electrical interference might be) they have a distinct, non-vertical incidence angle that rules out the possibility that they are electrical noise.

Finally, the goal of this work is to use ambient noise recording to image subsurface structure. One hypothesis is that we can "see" ambient energy diffract off near-surface structure and thereby learn about the near-surface. I have applied a simple hyperbola-summation method to data from the quarry blasts as well as ambient noise data in attempt to do this. At first glance the results are quite consistent. But a closer look shows that they are dominated by artifacts introduced by plane-wave energy which stacks in even when hyperbolic paths are used.

QUARRY BLAST RECORDINGS

While most of our recording was done during the night to minimize interference by cultural noise sources, we also recorded some daytime records. The USGS was going to set off several blasts in a quarry in Cupertino, CA (about 15 km away) for a research project of their own, and they kindly scheduled the blasts so that we could try to record them with our array. Figure **??** shows the survey area and indicates the direction of the quarry.

There were three blasts, a large "quarry blast", with 1500 pounds of explosives in a number of different shot holes (this blast is used by the quarry to dislodge rock) and two smaller single charges of 300 and 100 pounds that were set off for experimental purposes. USGS seismometers in the vicinity of our array clearly see the quarry blast (indeed, the quarry blast is visible for hundreds of kilometers) but not the smaller blasts.

Figure **??** shows portions of the seismograms recorded by one of our 169 groups for the three blast records. The quarry blast appears on the middle trace at around 10 seconds, but is not very obvious on a single-trace display. The smaller blasts arrive around 10.5 seconds on the other two traces, and are not at all apparent. The signal-to-noise ratio in our data, at least for daytime recording, is obviously quite small.

We were lucky to record these blasts at all. Our recording equipment consisted of 169 seismic group recorders (SGRs), each recording data on its own cassette tape and powered by a battery. This equipment was donated to Stanford by Amoco. The rechargeable batteries have a lifetime of about a day of normal operation. They worked fine for our nighttime recording, but had to sit using power until the middle of the next day for the blast recordings, and battery failure began to take its toll. About half the SGRs were still working for the first blast at 11 AM, and only 38 of the 169 were still working for the third blast at 12 Noon.

While the blasts are not readily apparent on individual traces, beam steering has been a very useful tool for detecting and locating them. Figure **??** gives a schematic view of the disc-shaped beam steering plots which will be used frequently throughout this paper. Stacking semblance is displayed as function of arrival direction (azimuth) and apparent slowness in polar coordinates. An apparent slowness of zero, corresponding to vertically incident events, is plotted at the center. The highest slowness value, at the edge, corresponds on these plots to an apparent velocity of 2 km/sec. These plots could also be described in terms of ray parameters p_x and p_y as shown in the figure, illustrating the equivalence of beam steering and slant stacking.

The orientation of the square in Figure **??** is the same as the orientation of the square indicating our array on the map in Figure **??**. Thus it is straightforward to relate azimuth directions on these beam steering plots to real-world directions. Figure **??** shows the result of beam steering the data from the three blasts and summing over 100 msec windows centered around the first arrivals from the blasts. It can be seen that the three blasts arrive from the same direction, all with an apparent velocity of around 4 km/sec. In Figure **??**, I gained the three panels independently so that the three blasts would have the same relative strength. In fact the blast from the middle panel, the quarry blast, is much stronger than the other two. If we were to perform the same summation over time as shown in Figure **??**, but using the entire 32 second records instead of a small window, the quarry blast would still dominate the middle plot, while the two smaller blasts would be lost in the background noise. Restricting the summation to a small window located at the right time has enabled us to see all three blasts.

While the blasts arrive in a consistent direction, that direction surprisingly differs considerably from the direction of the quarry, as can be seen by comparing these plots and the quarry direction indicated on the map in Figure **??**. The difference is on the order of 45 degrees. One possibility is that these first arrivals have traveled along a path that does not follow a straight line from the quarry to the array. The local geology gives some support for this theory. A direct path from the quarry to our survey would pass through large amounts of sandstone and conglomerate, while a path that initially turned further to the west and then came back to our array would remain for the most part in a faster, more well-consolidated basalt formation that parallels the San Andreas fault, which passes about 5 km to the southwest of our survey area. Another possibility is that the energy follows a more direct path and is then rerouted by the near surface, for instance by a tilted weathered layer beneath the survey.

Another interesting fact to note about the blasts is that there is strong evidence of energy from the blast following different paths to reach our array. Figure **??** shows many 100 msec frames from the large quarry blast following the first arrival shown in Figure **??**. All these frames have been gained identically, so the later arrivals are truly quite strong. I haven't shown frames from before the blast arrived, but they are relatively very quiet. Thus we can assume that all the strong events shown in Figure **??** are due to the blast. Note that this late-arriving energy comes in a variety of directions, some of it arriving in a direction much closer to the direction of the quarry. One possibility is that the earliest arrivals traveled through the faster basalts to the west, and then later energy traveling in the straight-line direction arrived.

Figure **??** shows the same sequence of plots following one of the two smaller blasts, record 44. Although these plots have been gained so that the first arrivals of the two blasts are similar in appearance, the smaller blast does not seem to have the same large amount of energy from the blast arriving at later times.

NEAR-VERTICAL EVENTS

One of the most interesting features of the dataset, discussed in SEP–60 (Nichols et al, 1989) was the abundance of near-vertically incident events in the nighttime records. These events are weak and not noticeable on individual seismograms. However, Lin Zhang showed that when the data were stacked along different trajectories (a special case of beam steering) these events showed up quite well.

Our first thought was that since the events are almost vertically incident, they must be due to some electrical interference. More careful beam steering now suggests that this is not so; these events seem to have a consistent direction of propagation that is close to vertical but not quite vertical. If that is so, they cannot be due to electrical noise.

Figure **??** shows the result of beam steering 12 different nighttime records. The entire 32 second records were used to produce each of these plots. The dominant feature of most of them, near the center, is the near-vertically incident events. While these events are close to the center, they are consistently just off-center. Their azimuth and apparent slowness indicate a fairly consistent arrival direction, from the east, with an apparent velocity of around 12 km/sec.

To illustrate why I think the events are not due to electrical interference, I took the same data and randomly re-ordered the positions of the 169 traces in our array. If the events are real, and not perfectly flat, then re-ordering the traces in this way should effectively eliminate them. Figure **??** shows the result of beam steering the re-ordered traces. There are some strong semblance values near the center, but they are not as strong as the values in Figures **??**. More importantly, they are no longer in the same place, but are mostly clustered around the center. This is precisely what we would expect to happen; the semblances are not going to drop to zero because there was strong, near-vertically incident energy present. After re-ordering it will still stack in to some extent. But the directional consistency should be, and is, lost. Thus I think it's clear that these events are not due to electrical interference.

Figure **??** shows the result of beam steering one of the 12 records, with and without trace re-ordering, at a larger scale. As is the case in Figures **??** and **??**, the two frames have been gained identically to preserve differences in semblance values. I think it's clear that re-ordering has reduced the semblance values considerably, and removed their directional dependence.

What could cause such events? If they were due to a surface source, the source would have to be very distant in order for the energy to arrive so steeply. Yet energy from any surface source that distant should be attenuated long before it reaches our array. Another possibility is that they are weak events coming from somewhere within the earth that typically go undetected but have been noticed by us because we have so many geophones in a compact area.

IMAGING

The ultimate goal of this work is to use ambient seismic energy to image the subsurface. In SEP–60, two approaches to this problem were proposed. Lin Zhang (Zhang, 1989) proposed that a reflection coefficient series could be recovered from autocorrelations of passive recordings. I proposed (Cole, 1989) looking for evidence of ambient energy scattering off near surface structure. Scatterers near the array should act as secondary sources. While we can't image these sources with conventional migration since we don't know the time at which they "explode", we should be able to see in the data the moveout patterns that identify the source location.

In SEP–60, the technique I used was to downward continue the wavefields, then sum power in the images at each depth, looking for the large power values that would result when energy is focused to a point in space, the source location. While that method is reasonable, I decided to backtrack and try to do the same imaging with a conceptually simpler scheme, used by Nikolaev (1987) to image scatterers using teleseismic data *and* ambient noise data with the NORSAR array.

In Nikolaev's scheme, we create a 3-D grid of possible scatterer locations in the subsurface. For each location, we find the moveout trajectory for energy coming from that point, and compute semblance over time along this trajectory in our data. We can then look at the average semblance over time, or the maximum semblance observed over all times, to get an idea of the scatterers that may lie in the subsurface.

An important first question is, given the size of our array, how far away can scatterers be identified as such? The limited size of the array will make it impossible to see any moveout for events coming from scatterers beyond a certain distance. Beyond this distance, scattered energy will be indistinguishable from plane waves. Nikolaev was using the NORSAR array, 110 km across, and was therefore theoretically able to image very deep structures. Our array is only 500 meters across, so our scattering analysis will be more localized. Figure **??** shows the moveout across the array for a scattered event versus distance of the scatterer from the array. This figure assumes a constant velocity of 2000 meters/sec, a very favorable choice. For higher velocities the dropoff will be sharper. The time difference drops to less than four milliseconds at around 5 kilometers from the array, so our scattering analysis definitely cannot go beyond that point. I have chosen one kilometer as an upper bound in the analysis that follows, to avoid coming too close to the limit.

Figure **??** shows the image that is obtained for the $z = 0$ depth level when this scattering algorithm is applied to portions of several different nighttime and daytime records. The x and y dimensions of the grid of scattering locations shown are three times the size of the survey. Thus points up to 750 meters from the array center are shown in this plot. The dominant features in this plot are the radial streaks. These are due to the fact that as we get further from the array center, our summation path becomes flatter and flatter. Eventually we reach the point where we are summing along a plane wave path, and from there out we would just get a radial streak.

Figures **??** and **??** show the results for depths of 500 and 1000 meters. A feature worth noting in all of these is the general agreement among the daytime blast records, and among the nighttime records, but not between the two groups. The reason for this is that what we are seeing when we sum along these hyperbolic paths is, predominantly, plane wave energy, which was quite different during day and night recording periods. In Figure **??**, I've performed the same computation as for Figure **??**, but I've summed along plane wave paths rather than hyperbolic paths. The fact that these two plots are quite similar is disappointing; it means that the algorithm is seeing mainly plane wave energy imperfectly stacked along hyperbolic paths, rather than scattered energy.

If we are to see scattered energy, probably it is necessary to filter out the strong plane waves present throughout our dataset.

CONCLUSIONS

Our passive dataset contains some interesting plane wave energy. The weak but abundant near-vertically incident events are surprising, but their origin remains a mystery. The quarry blasts show evidence of multiple propagation paths or scattering in their coda which merits more careful investigation.

Looking for scattered energy in the dataset is hampered by the fact that plane wave energy seems so strong that it overwhelms any scattered energy present. Some sort of filtering in velocity space can hopefully remove the plane wave energy and make scattered energy more apparent.

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