Why a big 2-D array to record microseisms?

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ABSTRACT

We plan to set out a two-dimensional seismic array, with our 200 group recorders. The initial goal is to measure an emergent angle spectrum of the microseismic noise. Our array will be designed to attenuate surface-travelling noise as much as possible. The dominant steeply emerging energy is expected to be generated by the ocean surf 20km distant. Such energy should enable imaging by the theorem that the (slant stacked) autocorrelation of the microseism is the reflection seismogram. Ultimately we hope to reproduce a portion of a conventional reflection image, and extend it in frequency or depth.

INTRODUCTION

Review

Theoretically, sound energy exists everywhere in the earth flowing in all directions all the time. We know almost nothing about this ambient acoustic energy.

Ideally, if we lay out a surface array of $14 \times 14 = 196$ geophones (or geophone groups) we should be able to observe beams at 14 emergent angles and 14 azimuths. In reality, we may be unable to see *any* beams emerging from depth because surface waves may be much stronger. The sidelobes from the surface waves could easily overpower our modest surface array. We'll consider it a success if we are able to see any deeply emergent beams at all. By "deeply emergent" we mean those waves with a surface velocity exceeding 2 km/sec.

Claim

We don't know that anyone has set out a two-dimensional array of the kind we envision, so even if our preconceived theoretical notions are wrong, our observations, by themselves, should be worthwhile.

But if the deeply emergent waves are measurable there are a variety of possibilities to use them to learn something of the deep interior of the earth.

Agenda

We plan to set up the array in a nearby pasture. After examining the results, a later project will be to redesign the array and use it another location where conventional reflection data quality is better.

PRECONCEPTIONS

Sources

Physically what are the sources? They could be earthquakes on the other side of the globe. Or they could be rain and thunder storms on the other side of the globe. But they needn't be so far away. Here at Stanford the source could be the omnipresent ocean waves pounding on the seashore about 20km distant. Theoretically, such waves descend about 10km before emerging here with a horizontal apparent velocity of about 5km/sec (an angle of about arcsin(1.5/5) or about twenty degrees off the vertical). The seashore also generates seismic surface waves, but we expect them to be absorbed by the propagation path. At the seashore we can hear abundant acoustic energy and of course this energy is distributed along the length of the coast, amounting to much energy in total. Further, we can calculate a substantial coupling deep into the earth. Experience with COCORP and regional seismology tells us that we can expect seismic-exploration frequencies to travel these kinds of distances. It is this expectation, along with our need frequently to explain our project to laymen, that caused us to dub our project the "ocean listen" project.

Noises

Earthquake seismologists are familiar with ocean wave noise—it is the principal limitation to earthquake observations at 0.1Hz. But we are hoping to make measurements in the 10-60Hz frequency range that is typical of reflection seismology.

Could we use conventional data before the first break? Probably not. The problem with conventional data is that the arrays are all designed for in-line noise. There is no discrimination against out-of-line noise. Even if our beach model were a perfect representation of reality, the noise arrival direction would range over 180° of azimuth. We can't ignore such massive smearing and we don't have an ingenious theory to overcome it.

What if we can't hear the ocean? A nearby professor of earthquake seismology, Kiyoshi Yomogida, says the dominant noise will be cultural, especially traffic. Such noises should travel nearly horizontally, unlike the energy we are interested in, so we have designed our array to do the best possible job of canceling such surface noise. Even so, surface noise may be so strong that it overwhelms our array. We'll be set back but not defeated if this is so. It means the angular spectrum of the noises will have no readily recognizable structure. So we won't know whether our data has any value at all unless we are able to make an image with crosscorrelations. In principal, correlations can average noises. So perhaps we will be able to use crosscorrelations to bring out the weak steeply emergent energy in the presence of the stronger surface noise.

After analyzing the results of our initial field work we expect to do a significant amount of theoretical work to re-design our geophone arrays. In this first experiment, we are planning to use 24 geophones in each group, so we are thinking of $196 \times 24 = 4704$ geophones (whew!) in all.

Images

Reflection images are generally strongest and most reliable at a traveltime depth of about one second. For initial experimentation we considered that the array size should be at least a Fresnel zone at one second. We perused the Yilmaz(1983) library of field profiles and found 700m to be about a typical Fresnel-zone size. From maps of the surrounding lands, we selected Cohn's pasture, an area with a minimum diameter about the required 700m, level enough for vehicles, with a friendly landowner (Stanford University), and conveniently located on the edge of the campus.

Geologic noise at our first site

A problem with Cohn's pasture is that it is reputed to be loaded with geological noise. Regionally we are in the collision zone between the Pacific plate and the North American continent. Where layered rocks are found, they rarely have lateral continuity beyond the outcrop. Where nearby shallow drilling for construction purposes showed nicely layered sandstones, later excavation showed sandstone blocks the size of a house (personal communication, George A. Thompson).

Since the geologic noise problem is a regional one we don't expect to be able to find any nearby site with good quality reflections. So we decided to do preliminary work at Cohn's pasture to try to understand the ambient seismic field and get experience at field operations. We don't expect to be able to make realistic reflection images at Cohn's pasture, whether or not we can hear the ocean. But from the Cohn's pasture work, we should be able to design parameters for work at a more distant site. Eventually we want a site with known good reflection seismology, where the local noise sources don't dominate the distant noise sources (after clever array designs and correlations).

EXPERIMENT DESIGN

Though we know nothing about the noise present at our site, some basic principles have guided us in designing our arrays for this first experiment. When we see what the noise looks like, perhaps we'll want to significantly re-design our arrays. But for now there are two main issues that have influenced our design.

First, there are some overriding logistical constraints. We have roughly 200 seismic group recorders or SGRs. Each SGR records one channel of data on its own cassette tape. A controller sends timing signals to all the SGRs via radio to synchronize recording. We can sum together the outputs of 12, 24, or 36 geophones to produce the signal recorded at an SGR. These numbers arise because there are twelve geophones per string in our equipment (with 50 feet of cable between geophones) and we can have up to three strings per SGR before the combined resistance of the cables becomes too large. The final logistical constraint in our survey area. The usable area is roughly 700m square.

The second consideration is one of sampling. The array must be designed to attenuate the surface noise, which can be discriminated against on the basis of apparent velocity. Surface waves will arrive with a velocity as low as 600 meters per second. To be able to attenuate these waves, we need to sample them unaliased. It is this requirement that sets the geophone spacing in our arrays. A wave travelling horizontally at 600 meters/second with a frequency of 40 Hz requires a geophone spacing of 7.5 meters or less to be unaliased. These are reasonable limits for the data we expect to record, so we have chosen a geophone spacing of 25 feet.

Array design

In this section, we discuss the design of the geophone arrays, the two-dimensional pattern of geophones whose outputs are summed together to produce a single channel. The design objectives for the arrays are that they should attenuate low apparent velocity noise coming in at all azimuths, they should be simple to lay out (since we will have to lay out nearly 200 of them) and they should not require too many geophones. While we can use 36 geophones per group, it means a lot more work than 12 or 24, so we need to be sure that the extra work is necessary.

Figures 1 and 2 show the array response for four different array designs, all having the geophone spacing of 25 feet discussed above. The responses are created using a method described by Cole (1987), and show the attenuation of a plane wave with an apparent surface velocity of 1000 meters/second as a function of frequency and azimuth angle. The gray level gives the attenuation, with darker shades of gray indicating greater attenuation. We want to attenuate noise travelling at such a low apparent velocity, and the array response plots indicate how good a job of attenuation a given array can be expected to do.

In Figure 1, two designs having 24 geophones per subarray are shown. At the top is the response due to a cross-shaped array. For frequencies below 10 Hz or so the cross does a good job, due to its large areal extent, but for higher frequencies its response is very dependent on azimuth. While energy coming in between two of the limbs at 45 degrees is attenuated very well, energy coming in the direction of one of the limbs in not attenuated by more than about 15 decibels. At the bottom is the response of a square array, a five by five grid of geophones with one missing at one corner. Its response is much better. It has some large sidelobes when approached from any of its four sides, but these cover a narrow range of frequency and azimuth.

At the top of Figure 2 is another square array, this time containing 36 geophones. The response is better than the 24 element square array at low frequencies (because of the greater spatial extent of the larger array), but the sidelobe problems remain. The marginal improvement suggests that for a square array, the extra work needed to use 36 geophones instead of 24 isn't worth it. At the bottom of Figure 2 is the response of a hexagonal array. Its response suffers less from sidelobe problems than the square, but its complicated layout is a drawback. Francis Muir has suggested tapering the square array to reduce the sidelobe problems.

Based on this analysis, we've elected to go with the 24 element square array in our first field experiment. This array is shown in Figure 3. With this design, the array centers are 125 feet apart. We plan to set up a 13x13 or 14x14 grid of these arrays. The exact size depends on the number of equipment failures we encounter. The 14x14 grid takes up an area 1625 feet square, which just fits within the boundaries of the land we have available.

We expect the setting up of the array to be a time-consuming process. In a small experiment it took three of us six hours to survey and lay out a 5x5 grid of arrays with only 12 geophones per array. Based on this it will take 200 man-hours to survey and lay out the array we have designed. We will call upon the full manpower of SEP to do this in one weekend.

IMAGES BY CROSSCORRELATION

An old mathematical theorem (Claerbout, 1968) provides inspiration for passive seismology. This theorem as published applies to plane wave seismograms. But with years of migration experience we now know how to do slant stacks and spatial Fourier transforms, and with modern recording densities, what was impractical in 1968, is now worth a serious try.

The theorem can be paraphrased, "autocorrelating data when the illumination is from below mimics illumination from above." Another paraphrasing is this, "the autocorrelation of the microseism is the reflection seismogram." This is inspiring because we know how to make earth images from reflection seismograms. Physically the autocorrelation may be interpreted as a crosscorrelation of two signals, first, the upcoming noises, which reflect back down from the earth's surface as a source signal, and second, the reflections from that source. Some of the mathematical requirements of the theorem may not be met in practice, on the other hand,

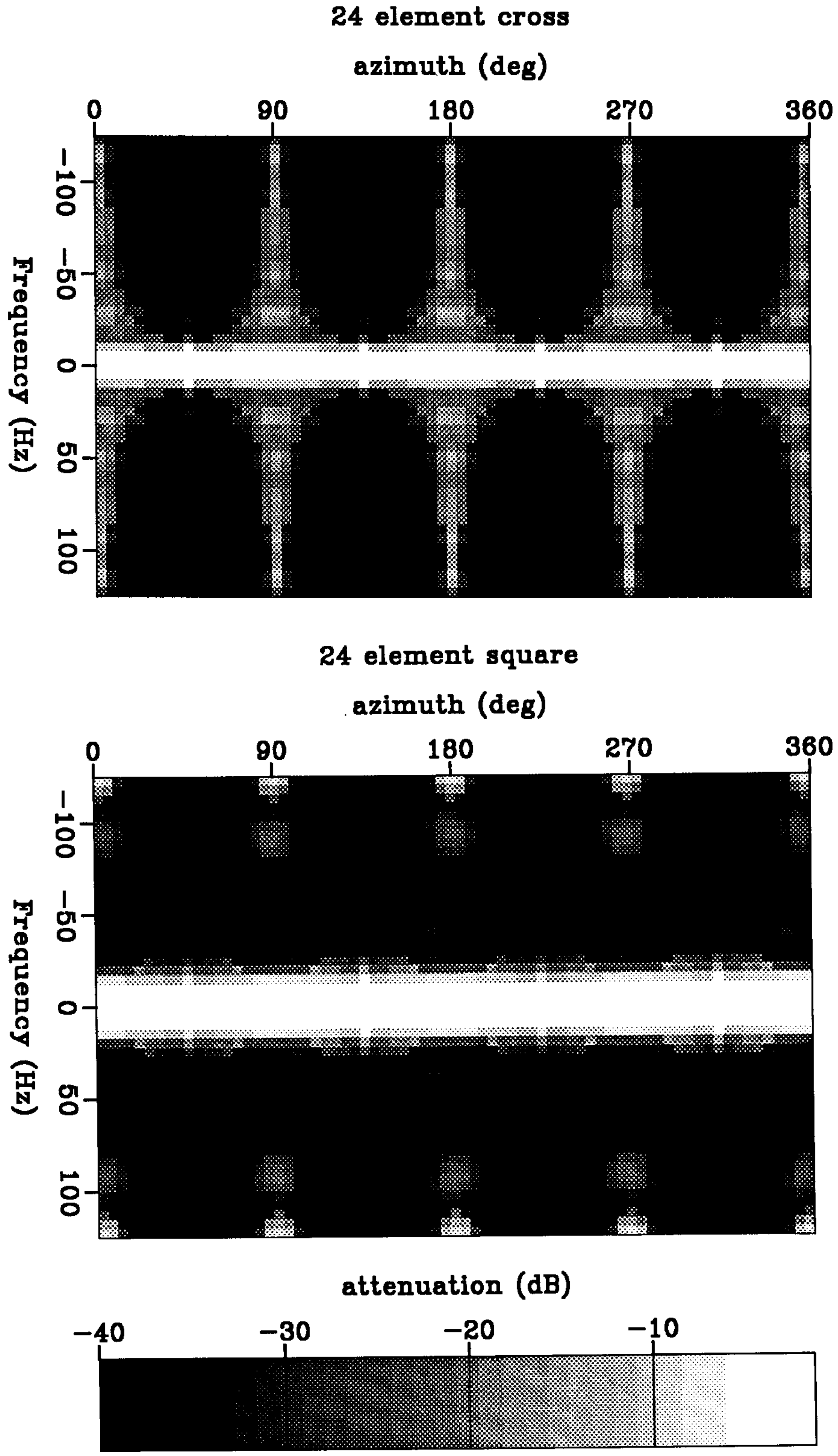

FIG. 1. Array response of a 24 element cross array (top) and a 24 element square array (bottom). The cross is good at attenuating low frequencies, but at higher frequencies its response is strongly dependent on azimuth.

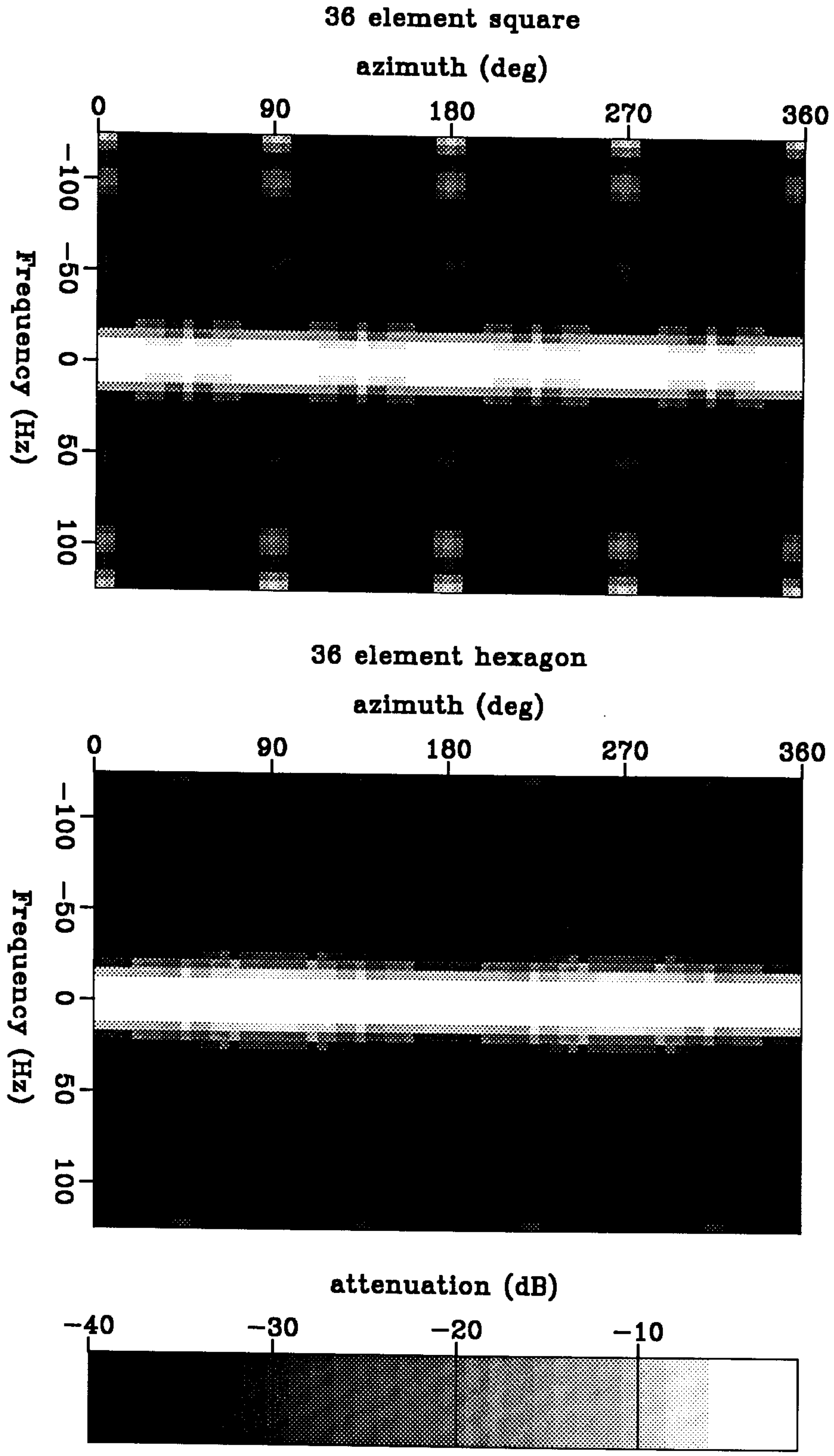

FIG. 2. Array response of a 36 element square array (top) and a 36 element hexagonal array (bottom). The square array offers only slight improvement over the 24 element square array of Figure 1. The hexagonal array suffers less from sidelobe problems but is difficult to lay out.

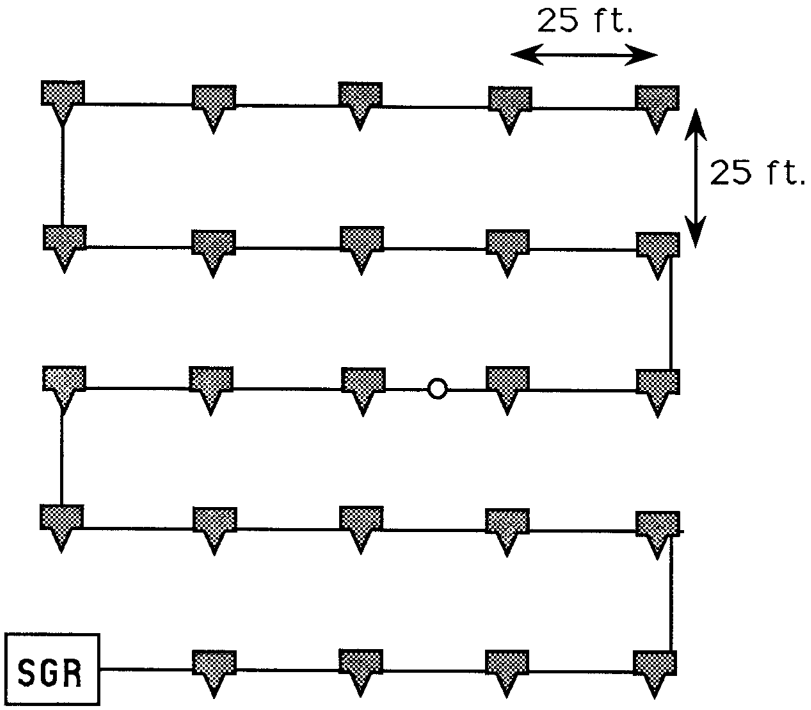

FIG. 3. The 24 element square array proposed for the experiment.

the concept seems sound, and it should be extendible to crosscorrelations between different beams. The lag of the autocorrelation gives the traveltime to the reflectors.

Statement of the theorem

Consider a layered acoustic media with vertically propagating plane waves. Consider only surface receivers. Define the (theoretical) reflection seismogram to be that where the source is an impulse time function at the surface. Define the (theoretical) earthquake seismogram to be that where the source is an impulse time function in the lower halfspace. The mathematical theorem says, **"The autocorrelation of the earthquake seismogram is the reflection seismogram."** (Superfluous details: (1) a scale factor, (2) only one side of the autocorrelation). Since the autocorrelation of white noise is an impulse function, and since the autocorrelation of microseismic noise is, on some physical scale, an impulse function, we have the hypothesis that **"the autocorrelation of the microseisms should be a reflection seismogram."** (Another superfluous detail is that the source wavelet on the reflection seismogram would be the autocorrelation of the noise).

Sketch of proof

Claerbout's 1968 proof of the theorem was lengthy. But in his 1976 textbook (FGDP) he provided a much simplified proof that can be paraphrased here.

Proof of the theorem goes in two stages. For the first stage you must use the energy flux theorem that energy is neither created nor destroyed by the medium.

Let U denote the Fourier transform of the upgoing wave and D be likewise for the downgoing wave. In each layer the upgoing wave spectrum $\bar{U}U$ minus the downgoing spectrum, say $\bar{D}D$, that difference times the material impedance is a constant function of depth. In the lower half space the upgoing wave vanishes and the downgoing wave, call it the escaping wave, is denoted by E. In the top layer the upcoming wave R changes polarity and reflects at the free surface giving the total downgoing wave $1 - R$. So the energy flux theorem gives

$$\bar{E}E = \bar{D}D - \bar{U}U$$

$$\bar{E}E = (1 - \bar{R})(1 - R) - \bar{R}R$$

$$\bar{E}E = 1 - \bar{R} - R$$

The second part of the proof of the theorem is that the escaping wave E is the same as the earthquake wave. This follows by reciprocity, although it is shown by detailed calculation in both the original paper and in FGDP.

To conclude the proof, in the time domain $\bar{E}E$ is the autocorrelation of the earthquake seismogram, i.e. the microseisms, and $\bar{R}+R$ is the reflection seismogram plus itself time reversed. The previous equation states the theorem.

Extensions of the theorem

Array design problems are likely to be the first problems in practice. Beyond this, however, a collection of interesting problems of a purely theoretical nature suggest themselves.

First, the fundamental autocorrelation theorem, can it be generalized to P-SV waves by considering two channel time series analysis? It would seem that it does, according to Frasier (1970). Looking back on Frasier's paper we should add that it applies to slant stacks, and that it should be possible to derive the result more simply from energy flux considerations (a la FGDP).

Second, what about an earth model that departs from the layered one? For small departures, the method of Estevez (1982) may be relevant.

CONCLUSIONS

It is too early to claim that passive seismic images could be better in some way than conventional images, but they would certainly differ, and could penetrate much deeper.

ACKNOWLEDGMENTS

We gratefully acknowledge the gift of the seismic group recorders from the Amoco company.

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