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Design considerations for experiments using novel seismic sources

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ABSTRACT

Two experiments using unconventional seismic sources have been studied recently at SEP, a passive seismic experiment and an experiment using a drill-bit source. The differences between these novel sources and conventional seismic sources place some added constraints on the experiment design. For instance, the ability to resolve the arrival direction of a wave in 3-D is essential if we are to discriminate the relatively weak (compared to conventional sources) source energy in the presence of nearby surface noise sources. From considerations such as this, I evaluate the design of the two experiments conducted to date and see how they could be improved upon.

INTRODUCTION

There has been some work done at SEP in recent years on recording seismic data without the use of a conventional source. Clement Kostov (Kostov, 1990) studied the use of the drill bit as a seismic source. In his work, the seismic energy generated by the drill bit takes the place of a conventional seismic source. The drill bit is an unconventional source in two respects. First, it is relatively weak compared to conventional sources such as Vibroseis and dynamite. Second, its behavior over time, or the source wavelet, is unknown.

I and others at SEP (Nichols et al, 1989; Cole 1989) have investigated the possibility of recording the ambient seismic wavefield and attempting to gain knowledge of the subsurface geology from it. This "passive seismic" problem suffers from the complications of the drill bit source, but suffers from an additional, obviously important, complication: we don't have a source at some known position in the earth.

These complications arising from the use of unconventional seismic sources are no surprise, and have guided the design of drill-bit and passive experiments from the start. Yet in all experiments performed to date, there have been limitations, usually imposed by constraints on time or equipment. My purpose in this paper is to spell

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out the requirements for experimenting with novel sources, see how these needs have or have not been met in experiments performed to date, and propose ways in which we any deficiencies in past work could be overcome in future experiments.

COMMON NEEDS

In the introduction, I stated two important ways in which novel seismic sources differ from conventional sources:

- The sources are relatively weak compared to conventional seismic sources.
- The source behavior over time (the source wavelet) is unknown.

These two complications imply that traditional methods will require some adaptation if we are to record and process data from unconventional sources effectively. In this section I will focus on how the unique nature of these experiments affects experiment design. I've come up with the following list of requirements for the design stage that follow directly from the special characteristics of the sources involved. For each, I've indicated why it is important, and whether this need was met in the drill-bit experiment studied by Kostov or in the passive experiment that I and others have described.

- **Directional resolving power.** Because the sources of interest are relatively weak, distinguishing them from the background will be more difficult than with conventional seismic data. Nearby surface noise sources could be as strong or stronger than the sources we are looking for, depending on local conditions. In conventional seismic profiling, the source is sufficiently strong that, in most cases, such out of plane energy is weak enough to be ignored. But with weaker sources, our experiments must be designed so that we can determine the direction of arrival of an incoming wave (and hence process to enhance or suppress it). A single line of receivers is inadequate for this purpose. Better is a 2-D or even 3-D array of geophones. If three-component phones are used, a 1-D array offers some directional resolving power, but as Martin Karrenbach and I showed (Karrenbach and Cole, 1989), a 2-D array is still far superior to a 1-D array when three-component phones are used.

  Did our previous experiments have sufficient directional resolving power?

  Drill bit experiment: **NO.** A 1-D array of single-component phones was used, and nearby surface noise sources were a problem.

  Passive experiment: **YES.** A 2-D array was used.

- **Knowledge of geology.** Some knowledge of the subsurface geology can obviously be quite helpful. In the drill-bit case, knowledge of the velocity model allows us to compute the expected moveout trajectory of drill-bit energy. In a passive experiment, some knowledge of subsurface structure might allow us to focus our attention on structures that are likely to scatter a significant amount of energy, and a velocity model would again be useful in determining moveout trajectories.

Assessment of previous work:

Drill bit experiment: **YES.**

Passive experiment: **NO.**

- **Receivers at depth.** Geophones located on the surface pick up surface-traveling noises such as wind noise and ground roll from nearby sources. In Kostov's drill-bit experiment, three geophones were located in a shallow well near the borehole. Kostov used these buried phones as a reference (relying on their insensitivity to surface noise sources) in a correlation procedure that reduced the influence of surface-traveling noise on his data.

  Assessment of previous work:

  Drill bit experiment: **YES.** However, three channels was an insufficient number. Kostov was unable to combine them effectively because there were so few. It would be better to have a downhole array, which could be beam steered along with the surface array to determine arrival direction of incident waves.

  Passive experiment: **NO.**

- **Adequate spatial sampling.** This is a concern in any seismic experiment, but I note it here to emphasize that the sampling must be adequate in **all** dimensions of the array. Otherwise events will be aliased. The required sampling interval in any dimension depends on the frequency of the incident energy and on its moveout. High frequencies and energy traveling closer to the horizontal direction necessitate a smaller receiver spacing. Given a maximum frequency of interest f_{max} and a minimum apparent velocity expected for incoming energy v_{min} the spatial sampling interval Δx required in one dimension is given by:

$$\Delta x < \frac{v_{min}}{2 f_{max}} \tag{1}$$

  Assessment of previous work:

  Drill bit experiment: **YES.** (But only in 1-D)

  Passive experiment: **YES.** In fact, our geophone spacing (25 feet) could have been larger. A minimum apparent velocity of 1500 meters/sec and a maximum frequency of 50 Hz gives a maximum allowable spacing of 15 meters. However, we were also limited in the overall size of our array, so we chose a finer spacing.

- **Sufficient aperture size.** Again, this is a concern in any experiment. Here we may need the aperture to be sufficiently large for a number of reasons. If we want to look at scattered energy, our array needs to be large enough to see the moveout of such scattered energy, which becomes small as the scatterer becomes distant.

Assessment of previous work:

Drill bit experiment: **YES.** (But only in 1-D)

Passive experiment: **YES.** Our array was 500 meters in diameter. This should allow us to resolve scatterers within about 1 kilometer of the array center. A larger array would be able to see scattering from farther away. Figure 1 shows the moveout across the array (in milliseconds) for scattered waves as a function of distance from the center of the array. For an array that is 600 meters in diameter, there is still 20 msec of moveout if the source is at a distance of 2 kilometers. Thus I feel confident in claiming that our 500 meter array is large enough to see scattering from within 1 kilometer.

Nikolaev and Troitskiy (1987) perform a similar scattering analysis using the NORSAR array, which is about 110 km across. They look for scattering from structures deep in the crust. However, they use lower frequencies. If we wish to look at typical exploration frequencies, we need to sample more finely in space, hence our arrays must be more compact and our targets much closer.

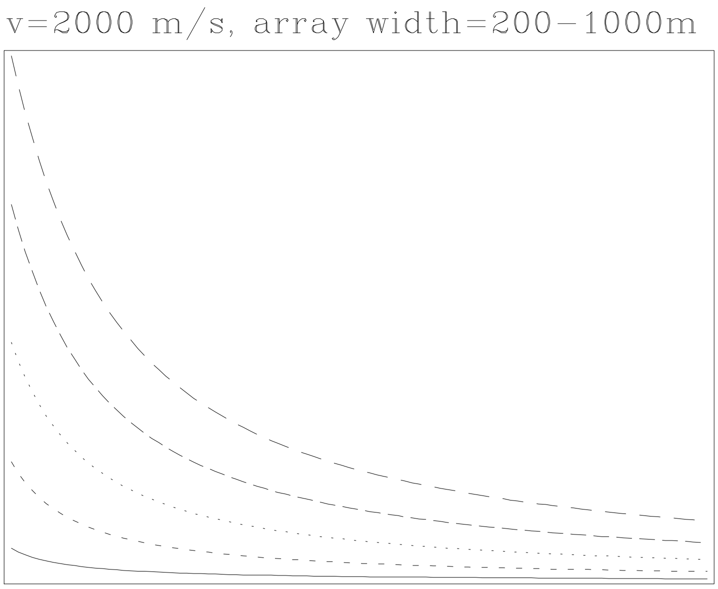

Figure 1: Moveout across the array (in msec) exhibited by energy from a point source versus distance from the array center for arrays of several different diameters - 200 (solid line), 400, 600, 800, and 1000 meters. These curves are for a constant medium velocity of 2000 m/sec. From these it is clear that there is a substantial amount of moveout for the 500 meter array used in our passive experiment for scatterers out to beyond 1 km distance. steve1-tdif [NR]

NEEDS PARTICULAR TO PASSIVE EXPERIMENTS

Some needs are particular to passive experiments only, and I have listed them here:

- **Source at known position for comparison.** The best measure of success is to be able to reproduce, even to a very limited extent, results obtained using a known source. This could be a Vibroseis or dynamite source from a conventional reflection experiment, or a source such as a drill bit.

  Assessment of previous work:

  Passive experiment: **NO.** We did have blasts set off in a quarry 25 km from the array which have been very useful, but a local source would have been more helpful.

- **Specialized recording/processing hardware.** Passive experiments mean long recording times. Whether we are waiting for relatively strong events, or recording many weak events and combining their results in processing, the volume of data produced by even a modest array would quickly become overwhelming. One solution is to collect as much data as possible and process it as best we can, but an alternative is to use specialized hardware. We might use a recording system that triggers on events of interest and records only at those times, or we might design a system that is processing the data in real time and accumulating a result, rather than storing all the data on tape. This second type of equipment, if available, might also be useful in drill bit work.

  Assessment of previous work:

  Passive experiment: **NO.** We recorded data for a total of approximately 30 minutes. Our array filled six large 9-track magnetic tapes in that short time. If we tried to record continuously for a long time, we couldn't keep up at the processing end.

NEEDS PARTICULAR TO DRILL-BIT AND SIMILAR EXPERIMENTS

One need comes to mind that clearly does not apply to passive experiments, but is appropriate for experiments such as those involving a drill-bit source.

- **Background noise recordings.** The fundamental problem is one of differentiating between the drill-bit energy and other energy in the background wavefield. It would be very helpful to have a recording of the background field, without the drill bit, in order to identify the ambient noise sources.

  Assessment of previous work:

  Drill bit experiment: **NO.** Such recording requires very little extra work, and might be very helpful in the processing stage. The background noise field could be analyzed, and then we would know what noise sources to expect in the drill-bit data.

FUTURE EXPERIMENTS

From the preceeding discussion, I suggest the following modifications for future experiments of the two types described here:

- Passive seismic experiments
  - Conduct survey in an area with some geologic information at hand, and preferably data from a reflection seismic or drill-bit experiment available for comparison.
  - Use three-component geophones.
  - If a well is available, place phones down the well to make the array 3-D and provide some channels relatively insensitive to surface-traveling noise.
- Drill-bit experiments
  - Use a 2-D surface array, of three-component phones if possible.
  - Record ambient noise while the drill bit is not operating, preferably with other drilling-related machinery operating.
  - If a well near the borehole is available, place phones down the well to make the array 3-D.
- Other experiments. We have limited ourselves to two types of experiments in this discussion, but it may be interesting to consider other sources whose properties are similar to those discussed here. Some examples are geothermal energy, steam injection, and pumps.

CONCLUSIONS

We have discussed, in rather general terms, the requirements on acquisition imposed by using novel sources such as a drill bit or ambient seismic energy. The most important requirement is that the array have the ability to locate incident events in 3-D, since these sources are relatively weak and nearby surface noise sources may overwhelm them unless we are able to distinguish the different arrivals and enhance those we are interested in while attenuating others. To do this we need (at least) a 2-D array of single-component geophones. Sampling and aperture considerations for the array are similar to those for conventional work. Finally, some knowledge of the subsurface geology, a tentative velocity model, or the availability of conventional data can be of great help in processing and provide a reference against which our results can be compared.

These conclusions are relevant to experiments using any source that has the properties described here – relatively low amplitude, an unknown source wavelet, and optionally an unknown source position. Such sources include drill bits, ambient energy, and other sources such as geothermal energy, steam flooding, or pumps.

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