Design and processing considerations for a passive seismic survey

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ABSTRACT

Passive seismology is seismology without the use of a controlled source to send sound waves into the earth. Interest in passive seismology originally grew out of the desire to detect and locate earthquakes and underground nuclear blasts. Teleseismic events contain information about the geology in the vicinity of the receivers, since the teleseismic energy will reflect, refract, and diffract off structures beneath the recording location. Microseismic activity near the recording location will provide energy that may be useful as well. Signal to noise ratios are typically small compared to controlled-source surveys, so sophisticated processing techniques are needed to overcome noise contamination and image the subsurface structures. This paper is a brief review of field and processing techniques that have been used in passive seismic experiments to date. Also included are some thoughts on how past work needs to be supplemented to meet the particular requirements of exploration seismology.

INTRODUCTION

A variety of concerns must be addressed to be sure that passive seismic techniques are appropriate for a given objective. Some concerns are exactly parallel to concerns in conventional controlled-source seismology, such as imaging techniques. Given reflections and diffractions off subsurface structures propagating to the surface and being recorded, how do we reconstruct the picture of the subsurface reflectors and scatterers? Some considerations will be similar to those in controlled source seismology, but of greater or lesser importance in the passive case. An example is seismic array processing. With a controlled source, applying the correct time delays and summing the signals from a number of receivers may be adequate to give a sufficiently strong signal on output, yet with the smaller signal to noise ratio of passive seismology, multichannel filtering techniques that exploit the lack of spatial organization of the noise may be crucial if any useful result is to be obtained. Still other concerns will be unique to the passive seismic problem. For example, what coherent sources of energy are available, how strong are they relative to the ambient noise, and with what frequency do such events occur?

This paper is a first attempt at describing these concerns. I begin by reviewing some of the work that has been done in passive seismology, illustrating some of the main issues and how they have been addressed in the past. I conclude by discussing the peculiarities of passive seismic exploration, hoping to begin to determine whether our standard processing techniques are adequate for passive seismic exploration, and if not, what other techniques are necessary.

MAIN CONCERNS

What are the sources?

The most obvious and perhaps most important question to ask about passive seismology is, what are the energy sources to be used in imaging and are they strong enough compared to ambient noise? There are some obvious sources of body wave energy present in the earth in the absence of a controlled source. Teleseismic events from earthquakes at great distances are strong enough that they can be recognized as such by a single seismograph. Experiments have successfully used teleseismic events as sources. Troitskiy *et al* (1981), Aki (1973, 1977), and Berteussen *et al* (1975) all successfully used teleseismic P-waves to image structures in the lower crust and mantle by viewing the diffraction of these waves off subsurface scatterers. These diffractions are observable in the coda of the recorded teleseismic events, following the direct arrivals. Their experiments were performed using large-scale seismic arrays such as NORSAR, the Norwegian seismic array, and LASA, the large aperture seismic array located in Montana. Such large arrays exploit the fact that waves from distant sources will be coherent over large distances (for example the diameter of the NORSAR array is approximately 110 kilometers) but that noise will not. The arrays are only able to see scattering off fairly deep structures, on the order of 100 kilometers, because of their coarse spacing. Diffractions off nearer-surface events are aliased. If we are to image near-surface diffractions for exploration purposes, then, more compact arrays must be used.

Another useful source of energy is local earthquakes. Especially useful are the aftershocks following large earthquakes, as they provide a large number of sizeable, localized events in the days or weeks following a large earthquake. James *et al* (1987) used the aftershocks from a 1983 earthquake at Borah Peak, Idaho to image subsurface structures ranging in depth from 18 to 28 kilometers using reflected shear waves. In 10 days of recording they obtained 1000 useful aftershock events (all with magnitude 2 or less), using nine three-component seismographs covering a ten by ten kilometer area.

They determined the hypocenter of each aftershock, then using a rough velocity model corrected to a single source depth, so that all events appeared to have a common origin time. Then the data were stacked, yielding coherent reflections that were not visible on the prestack traces. In their paper, they suggest a number of refinements that may enhance future results, such as prestack crosscorrelation to eliminate errors in the source depth correction, correction for varying source wavelets (due to different focal mechanisms) that also cause mis-stacking, and deconvolution. The similarities between this experiment and conventional reflection seismic exploration are numerous, supporting the belief that passive techniques may be useful for exploration.

Aki (1969) also used aftershocks from large earthquakes, inferring from the uniformity of the coda with distance from the epicenter a uniform distribution of randomly-located subsurface scatterers.

Geothermal activity also is a source of seismic energy. Douze and Sorrells (1972) found a correspondence between heat flow anomalies associated with known areas of geothermal activity and anomalies in the ambient noise levels. Geothermal activity has a distinct spectrum of roughly 2–8 Hz that is often exploited in locating such energy. To my knowledge, no study has successfully used geothermal activity for imaging purposes.

There are a number of other possible sources of seismic energy that can be considered. Nikolaev and Troitskiy (1987) used seismic energy generated by a hydroelectric power plant to image subsurface structures via scattering. They also discussed the possibility of microseismic events generated by strain variations that accompany free oscillations of the earth. There is also some evidence (McLaughlin and Jih (1986)) that body waves are generated from Rayleigh waves scattered off rough surface topography.

In summation, there are many sources of seismic energy in the earth, some of which have already been used to image subsurface structures. Two important questions are, how strong are these sources compared to the background noise, and how long do we have to record to obtain sufficient data redundancy? Earthquake sources are often sufficiently strong to be resolvable, though as will be seen in the next section, sophisticated processing is often required to overcome the noise. Even when observing aftershocks following a large earthquake, earthquakes are always infrequent enough that some sort of real-time event detector that triggers recording is an important part of such a survey. Non-earthquake sources are too poorly understood to say much about their relative amplitudes or frequency.

How to suppress noise?

Geophone arrays are used to enhance signal in the presence of noise. If the signal is sufficiently strong, simply summing the channels of the array to produce an output will preserve the signal. In cases where the signal is not as strong, it may be important to shift the signals before summing to remove any time delays, so that the signals from the different geophones reinforce one another. If the signal to noise ratio is even smaller, some sort of multichannel processing may be necessary in order to bring out the signal.

Bungum *et al* (1971) give an interesting description of the beam steering used to detect events at NORSAR in real time. A recursive filter is used prior to beam steering to reduce noise. Burg (1964) describes a method of least squares multichannel Wiener filtering that was used by Backus *et al* (1964) to enhance mantle P-waves in the presence of noise. In Burg's method, a different frequency-dependent filter is applied to each receiver prior to summing. The filters obtained, and their success in suppressing noise, depend on the spatial organization of the noise. Capon *et al* describe a maximum-likelihood multichannel filtering method that also applies a different filter to each trace prior to summing. The filters are constructed based on several statistical parameters determined from the data. Capon makes the important point that such multichannel filtering is especially important for small arrays because noise is more organized on small arrays. We have seen already that searching for near-surface scattering using teleseismic and microseismic events will require more compact arrays than those used for deep crustal and mantle studies. This suggests that multichannel filtering techniques will be especially important if passive seismology is to be used in exploration.

Imaging techniques

Many imaging techniques that have been used for passive seismology have already been used in conventional exploration seismology. Aki (1973, 1977) inverts travel times to determine the three– dimensional velocity structure of the lithosphere. He concludes that Chernov's theory that anomalies in travel times and amplitudes can be caused by small scale, random inhomogeneities in the subsurface can largely explain the observed time and amplitude anomalies. Troitskiy *et al* (1981) use diffraction tomography to image subsurface scatterers. Nikolaev and Troitskiy (1987) compute semblance over travel time trajectories that would result from diffractions at each point in a subsurface grid, using a crude velocity model to compute the trajectories. James *et al* use a variety of standard seismic processing techniques (crosscorrelation, filtering, stack, deconvolution) in their processing of earthquake aftershocks.

Thus it seems that once events are brought out from the background noise, conventional processing techniques can be applied. There appears to be room for some advances. For example, Troitskiy *et al* use only one frequency in their tomographic technique due to noise problems. Perhaps there are ways of overcoming this limitation.

Why passive seismology?

The discussion above suggests that, given the right conditions, it is possible that passive seismic techniques can be applied to seismic exploration. An important question is, why would we ever choose to perform a passive seismic survey? Surely anything seen by such a survey would be illuminated much better if a controlled source were used. However, if its limitations are overcome, passive seismology offers a number of advantages over controlled-source techniques. Obviously, it is much less expensive than controlled-source techniques. Also, passive surveys can be conducted in areas where controlled-source surveys are not feasible, such as extremely mountainous terrain, or where the geology is so complex that source energy cannot penetrate, as in cases where sediments are overlain by volcanics. The field logistics of passive surveys are much simpler than those for controlled-source surveys. Several of these advantages are noted by James *et al*, along with some advantages that are specific to their surveys using microearthquake sources. Such surveys offer a high degree of data redundancy, large sources that are efficient generators of shear waves, and an areal distribution of events that provides excellent three-dimensional subsurface coverage.

CONCLUSIONS

Passive seismology has already been used successfully to image subsurface structures in a variety of different experiments. Application of passive seismic techniques to seismic exploration will undoubtedly entail some problems not encountered in these other experiments. Yet the many similarities between the processing tools used in passive seismic experiments to date and those used in conventional exploration seismology suggest that there is good reason to hope that processing can overcome these problems, and that passive seismology can be a useful exploration tool.

The references, which have been discussed only briefly here, should serve as a good starting point for anyone interested in exploring this topic further.

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REFERENCES

Aki, K., 1969, Analysis of the seismic coda of local earthquakes as scattered waves, Journal of Geophysical Research, **74**, 615-631.

Aki, K., 1973, Scattering of P waves under the Montana LASA, Journal of Geophysical Research, **78**, 1334-1346.

Aki, K., 1977, Determination of the three-dimensional structure of the lithosphere, Journal of Geophysical Research, **82**, 277-296.

Backus, M., Burg, J., Baldwin, D., and Bryan, E., 1964, Wide-band extraction of mantle P waves from ambient noise, Geophysics, **29**, 672-692.

Berteussen, K.A., Christofferson, A., Husebye, E.S., and Dahle, A., 1975, Wave scattering theory in analysis of P-wave anomalies at NORSAR and LASA, Geophysical Journal of the Royal Astronomical Society, **42**, 403-417.

Bungum, H., Husebye, E.S., and Ringdal, F., 1971, The NORSAR array and preliminary results of data analysis, Geophysical Journal of the Royal Astronomical Society, **25**, 115-126.

Burg, J.P., 1964, Three-dimensional filtering with an array of seismometers, Geophysics, **29**, 693-713.

Capon, J., Greenfield, R.J., Kolker, R.J., and Lacoss, R.T., 1968, Short-period signal processing results for the large aperture seismic array, Geophysics, **33**, 452-472.

Douze, E.J., and Sorrells, G.G., 1972, Geothermal ground-noise surveys, Geophysics, **37**, 813-824.

James, D.E., Clarke, T.J., and Meyer, R.P., 1987, A study of seismic reflection imaging using microearthquake sources, Tectonophysics, **140**, 65-79.

Lacoss, R.T., Kelly, E.J., and Toksöz, M.N., 1969, Estimation of seismic noise structure using arrays, Geophysics, **34**, 21-38.

McLaughlin, K.L., and Jih, R.S., 1986, Finite difference simulations of Rayleigh wave scattering by 2-D rough topography, Air Force Geophysics Laboratory, Scientific Report #3.

Nikolaev, A.V., and Troitskiy, P.A., 1987, Lithospheric studies based on array analysis of P-coda and microseisms, Tectonophysics, **140**, 103-113.

Troitskiy, P., Husebye, E.S., and Nikolaev, A., 1981, Lithospheric studies based on holographic principles, Nature, **294**, 618-623.