CONF-8409115--1

FIELD IMPLEMENTATION OF GEOPHYSICAL DIFFRACTION TOMOGRAPHY*

CONF-8409115--1

DE84 017594

A. J. Witten

S. S. Stevens

Energy Division

Oak Ridge National Laboratory

Oak Ridge, Tennessee 37831

*Research sponsored by the ORNL Low-Level Waste Management Program Office, U.S. Department of Energy under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

FIELD IMPLEMENTATION OF
GEOPHYSICAL DIFFRACTION TOMOGRAPHY

Alan Witten
Scott Stevens
Oak Ridge National Laboratory

ABSTRACT

Geophysical diffraction tomography is a new technique that shows promise as a tool for quantitative subsurface (below-ground) imaging. The approach being used is based upon the filtered backpropagation algorithm, which is a mathematical extension of the reconstruction software used in conventional X-ray CAT scanners. The difference between this method and existing methods is that the new algorithm rigorously accounts for diffraction effects through an exact inversion of the wave equation. This refinement is necessary in that it admits the use of acoustic and long-wavelength electromagnetic waves, allowing tomography to be taken from the laboratory to the field.

ORNL's effort in geophysical diffraction tomography involves reducing the filtered backpropagation algorithm to practice. This requires the design and construction of field instrumentation as well as the development of an improved algorithm. The original algorithm requires the imaged region to be illuminated by plane waves. This requirement simplifies the algorithm but complicates its field implementation in that plane waves are difficult to generate. Consequently, ORNL has been working to generalize the filtered backpropagation algorithm to allow a broader range of incoming wave fields which can more easily be realized in the field. The instrumentation aspects involve the selection of appropriate sonic sources and receivers along with the development of a state-of-art, portable, computer-controlled, multichannel data acquisition system.

BACKGROUND

A technique of recent interest in subsurface imaging is geophysical tomography. This technique is an extension of medical X-ray tomography. While this technique is an accepted laboratory and clinical method, there are a number of requirements which limit the direct applicability to geophysical problems. For computer-aided X-ray tomography, data from a single illumination of an object can be backprojected (Kak, 1979) to provide a partial reconstruction or image of the object. Uniqueness considerations require illuminations at many viewing angles in order to obtain an adequate reconstruction. Thus CAT scanners are devices free to rotate about the object being imaged allowing illuminations over a 360° range of viewing angles. The geophysical setting does not practically allow an unrestricted range of viewing angles, and as a result reconstructions may be distorted or misleading.

Witterholt et al. (1981) used an X-ray algorithm to obtain tomographic reconstructions for steam flood tests at the McMurray Tar Sands. These experiments were performed with electromagnetic waves at radio frequencies. The results obtained delineate suspected steam zones; however, these results could only be qualitatively verified by conventional well logging techniques. While it is believed that the identified steam zones actually exist, the accuracy of the representation of steam zone boundaries is suspect as a result of both the limited range of viewing angles and the use an X-ray algorithm in a diffracting medium.

The necessary use of longer wavelength acoustic or electromagnetic waves in geophysical applications (as compared to X-rays in medical tomography) results in diffraction effects which cannot be ignored in all but the most homogeneous geophyscial settings. Dynes and Lytle (1979) suggest that straight-line (non-diffracting) theory is adequate when variations in wave speed are 16% or less and that this approach is marginal for wave speed changes up to 33%. Considering that changes in wave speeds of 100% over several wavelengths are not uncommon, it is important to account for diffraction in the reconstruction algorithm.

Devaney (1982) developed a filtered backpropagation algorithm which allows tomographic reconstructions at longer wavelengths by rigorously accounting for diffraction effects. This is accomplished by an exact inversion of the reduced wave equation subject to a small scatter approximation. In contrast to the straight-line type reconstructions of X-ray tomography in which the received signal is backprojected from the receiver array, the filtered backpropagation algorithm uses the wave equation to propagate the signal from the receiver array back into the diffracting media. The backpropagation algorithm not only accounts for diffraction effects but also provides more information per viewing angle than the backprojection approach. As a result, the filtered backpropagation algorithm requires fewer viewing angles to provide an adequate reconstruction.

This paper presents the current status of a project directed towards reducing geophysical diffraction tomography to practice. This effort involves the development of improved reconstruction algorithms, the design and fabrication of a field data aquisition system, and the software necessary to control data collection and reduce the collected data. The proposed configuration is shown in Figure 1. Sonic sources are distributed along the ground surface and the diffracted (frequently termed refracted in seismic applications) signal from these sources is monitored on a receiver array located in an adjacent borehole.

This paper provides an overview of the reconstruction algorithm, a discussion of parameters which have been considered in developing a field implementation plan, and a conceptual design of the data aquisition system.

THE ALGORITHM

Tomographic reconstructions are obtained by the application of a mathematical technique known as the filtered backpropagation algorithm (Devaney, 1982). The manner in which this algorithm works is best understood by first considering the foreward wave propagation problem. For a known wave source illuminating an inhomogeneous propagating medium of known characteristics, it is possible to, at least in principle, solve the governing wave equation to predict the diffracted wave field anywhere in the region of interest. In trying to perform subsurface imaging, the wave source is presumed to be known, however, the characteristics of the propagating medium are unknown. In fact, it is these characteristics which must be determined to produce subsurface images. In this case, however, the diffracted wave field is measured. With the source characteristics known and the diffracted wave field known, it is possible to solve the wave equation for the local characteristics (wave speed, density, rigidity, compressibility) of the diffracting medium. This then may be considered backpropagation in that the received signal is propagated backwards via the wave equation through the diffracting medium mapping characteristics of this medium between the receiver array and the source.

The filtered backpropagation algorithm requires illumination of the region of interest by plane waves. A plane wave is a mathematical artifact which, in practice can only approximately be generated. The best method for creating a wave which locally "looks like" a plane wave is to place a point source very far from the region of interest. This provides a spherical wave front with a radius sufficiently large that it is essentially flat over a limited extent. This approach is not feasible for geophysical problems. If sources are located at or below the ground surface, the source/receiver spacing would be so large that all but the lowest frequencies would be attenuated. Locating sources above the ground surface will result in an excess loss of wave energy through reflection at the air/ground interface. Another means of generating approximate plane waves is by a superposition of point sources. This method is known as slant-stacking (Schultz and Claerbout, 1978). While this approach is feasible for geophysical tomography, it produces spurious phase variations within the plane of the wave resulting in the equivalent of a noisy signal.

To avoid the problems associated with plane wave generation, the filtered backpropagation algorithm was modified to allow arbitrary source distributions. This new algorithm may appropriately be termed the generalized backpropagation algorithm. Software has been developed to implement this algorithm for point source configurations, since point sources are the most convenient to generate in the field.

IMAGE RESOLUTION

The backpropagation algorithm requires that reconstructions be performed at a fixed wave frequency, and field implementation necessitates sampling the diffracted signal at a finite number of points. These factors must be considered when developing a plan for field implementation of geophysical diffraction tomography. Specifically, in developing such a plan the resolution required must first be identified and, from this, a minimum wave frequency and receiver spacing must be determined. It may not be feasible to achieve these performance objectives, in which case the image resolution would be compromised. For example, attentuation of wave energy may require that reconstructions be performed at a wave frequency less than that required for the desired resolution. Similarly, cost considerations could limit receiver density and this could also impact image resolution.

A parametric study has been performed to quantify the influence of wave frequency and receiver spacing on the image resolution. Based on the results of this study, the minimum length scale which can reliably be resolved is (1) twice the distance between adjacent receivers, and (2) one quarter of the wavelength of the incident wave. To demonstrate the influences of these two parameters on image quality, consider a homogeneous host material and a single circular inclusion having different wave propagation characteristics. The refractive index may be defined as zero in the host material and a constant non-zero value within the circular inclusion. A plot of refractive index along a line passing through the center of the inclusion would have a "top hat" shape. Figure 2 shows the results of the backpropagation algorithm as applied to the situation described above. In this case, the reconstruction was performed at a sufficiently high frequency and receiver density to satisfy the previously described resolution requirements. This figure clearly shows that the "top hat" shape has been accurately reproduced. In contrast, Figure 3 shows a reconstruction performed with an adequate receiver spacing but at a wave frequency which is below the recommended minimum. Here the transition from the host medium to the inclusion is not sharp. Thus performing reconstructions at a frequency too low for the desired resolution will result in a blurred image. Figure 4 is a reconstruction performed at a sufficiently high wave frequency but with an inadequate receiver density. The result is that the "top hat" has degenerated into a triangle.

The implication of these limitations on the shallow subsurface imaging of low-level waste disposal sites has been considered. It is anticipated that reconstructions could only be performed at frequencies greater than 200 Hz. Assuming that 64 receivers are distributed over a 10 m depth, the smallest object which can be resolved will have a length scale of about 30 cm. In this case the resolution is limited by receiver spacing, not by wave frequency, so that smaller inclusions could be resolved with more receivers. Wave frequencies greater than 500 Hz may be attenuated by the buried waste. At this frequency, the wave frequency limitation would allow the resolution of objects no smaller than 12 cm; however, this resolution would require approximately 150 receivers.

FIELD INSTRUMENTATION

In order for the backpropagation algorithm to be a viable tool for subsurface imaging, field instrumentation must be compatible with the data requirements of the algorithm. While there exist similarities between data collected for conventional seismic techniques and that required for geophysical tomography, the demands of tomographic implementation are more stringent requiring a more sophisticated data aquisition system.

The factors which must be considered are those related to the required resolution as discussed in the previous section, along with the signal-to-noise ratio of the system. Within the scope of the current project it is not possible to fabricate a system which will satisfy all these requirements for all conceivable applications. Thus, the design objectives are directed toward system flexibility and expandability.

Extremely high resolution reconstructions require a large number of receivers and a high wave frequency. Attenuation of high frequencies suggests that reconstructions will be performed near the weak signal limit where singal-to-noise ratio is the dominant concern. In light of this, it is deemed more important to dedicate available resources to the quality of each channel even if it is at the expense of the total number of channels. Allowing for the future addition of channels leads to expandibility considerations. Signal-to-noise considerations suggest that it is desirable to perform reconstructions at the lowest possible wave frequency allowable for a specified resolution. Since this will vary with the particular application, the data aquisition system must have the flexibility to accomodate a range of frequencies.

Based upon the expandibility, flexibility, and signal-to-noise ratio considerations, a conceptual data aquisition system design has been developed. This is schematically represented in Figure 5 (see Figure 1 for the physical configuration of the system). As can be seen in this figure, the system design allows for most data aquisition functions to be performed independently for each channel. The elements of this system which are emplaced in the borehole are a hydrophone/preamp pair for each channel. These are commercially available and offer good frequency response in the range from several Hz to several kHz. Each channel will also have components above the borehole which include an amplifier, an analog-to-digital (A/D) converter, a single board computer (SBC), and local memory. The SBC will control the local functions of each channel including sampling frequency and gain ranging. The amplifier is included both to provide additional amplification of the signal and to facilitate gain ranging which is more difficult to control on the remotely located preamp. Local memory is provided to allow the short-term retention of received data. This avoids potential sampling frequency limitations of a more conventional multiplexed system.

The entire multichannel data aquisition operation will be controlled by a supervisory computer. This computer will sequence the "firing" of each source. After each source "firing" the computer will control a channel-by-channel downloading of the local memory and experiment-specific parameters to a mass storage device. The supervisory computer will also have limited data analysis and display capabilities to help assure that no malfunctions occurred.

Anticipated sources are impulsive sonic sources commonly used in geophysical exploration. This includes a variety of explosives as well as devices which propel a striker against the ground or a plate. The selection of a particular source will be based upon the needs of a given application.

CONCLUDING REMARKS

An implementation plan has been developed for reducing geophysical diffraction tomography to practice. This has led to an improved reconstruction algorithm and a conceptual instrumentation system design consistent with the needs of a broad range of field applications. Figure 6 is an example of a type of reconstruction and image quality which can theoretically be achieved. While this reconstruction is based on analytically-derived data, rather than field data, the parameters used are consistent with those of the data aquisition. It should be noted that this is a development exercise and field experience could indicate the need for refinements in both the reconstruction algorithm and system design before field reconstructions will yield images of the quality shown in Figure 6.

There are additional problems which are anticipated but these can only be addressed in the field. Problems of this type include extraneous noise, coupling between the ground and sources and receivers, and signals diffracted from subsurface feature outside of the imaged region. While potential solutions to these problems have been contemplated, resolution of these problems can not be achieved until their nature and magnitudes are quantified.

REFERENCES

Kak, A. C., "Computerized Tomography with X-ray Emission and Ultrasound Sources," Proc. IEEE, Vol. 67, 1979, pp 1245-1272.

Witterholt, E. I., J. L. Kretzsehmar, and K. L. Jay, "The Application of Crosshole Electromagnetic Wave Measurements to Mapping of a Steam Flood," Proc. Petroleum Society of CIM, Paper No. 82-33-81, 1981.

Dines, A. J., and R. J. Lytle, "Computerized Geophysical Tomography," Proc. IEEE, Vol. 67, 1979, pp. 1065-1073.

Devaney, A. J., "A Filtered Backpropagation Algorithm for Diffraction Tomography," Ultrasonic Imaging, Vol. 4, 1982, pp. 336-350.

Schultz, P. S., and J. F. Claerbout, "Velocity Estimation and Downwind Continuation by Wavefront Synthesis," Geophysics, Vol. 43, 1978, pp 691-714.

FIGURE CAPTIONS

Figure 1. Field configuration for the implementation of geophysical diffraction tomography.

Figure 2. Reconstruction of a circular disk evaluated along a line passing through the center of the disk for an adequate wavelength and receiver density.

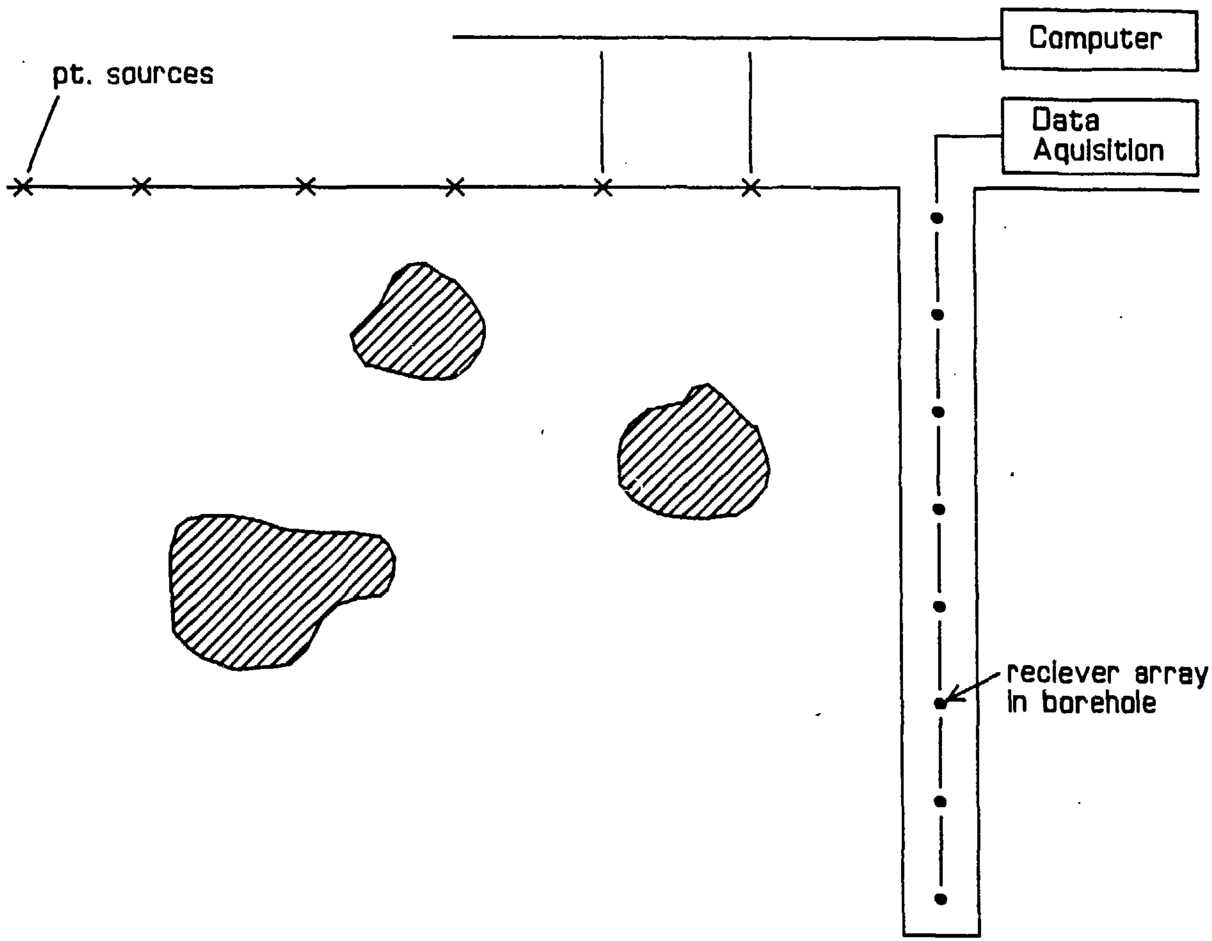
Figure 3. Reconstruction of a circular disk evaluated along a line passing through the center of the disk for an adequate receiver density but a wavelength which is to long.

Figure 4. Reconstruction of a circular disk evaluated along a line passing through the center of the disk for an adequate wavelength but an insufficient number of receivers.

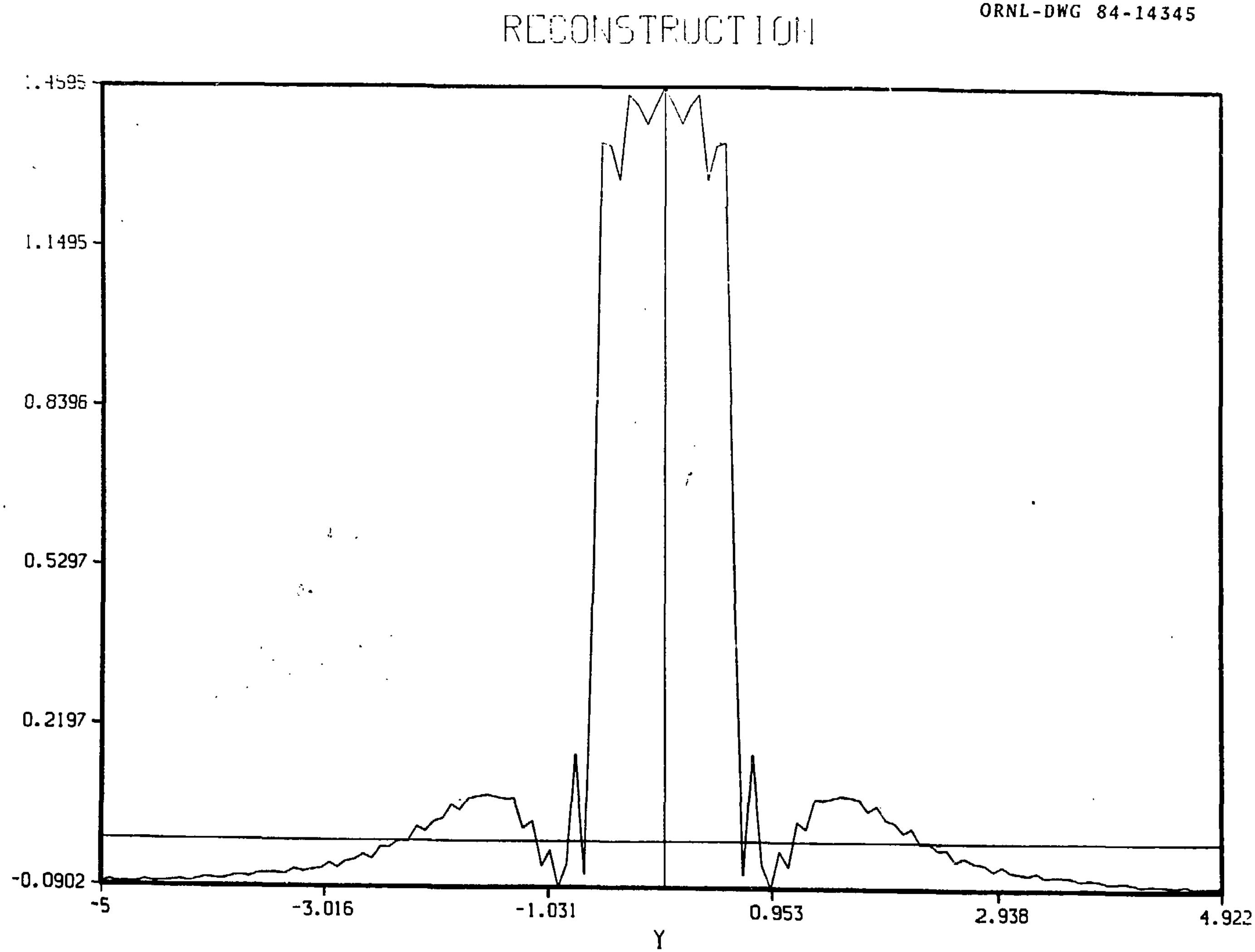
Figure 5. Schematic representation of the conceptual field instrumentation design.

Figure 6. Computer-generated reconstruction showing circular buried waste inclusions (dark shading) distributed above (white) and below (light shading) the water table.

ORNL-DWG 84-14333

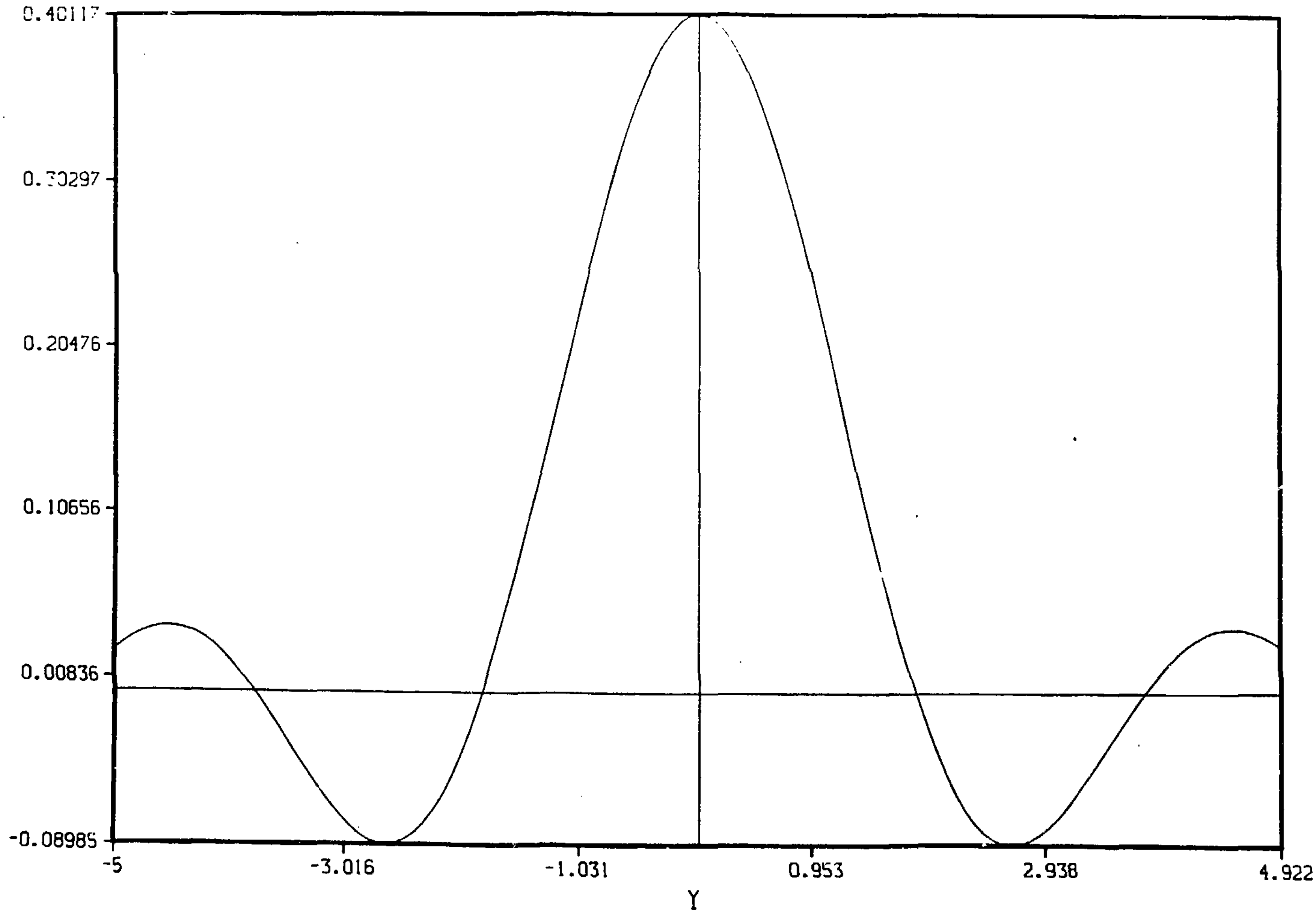


ORNL-DWG 84-14345

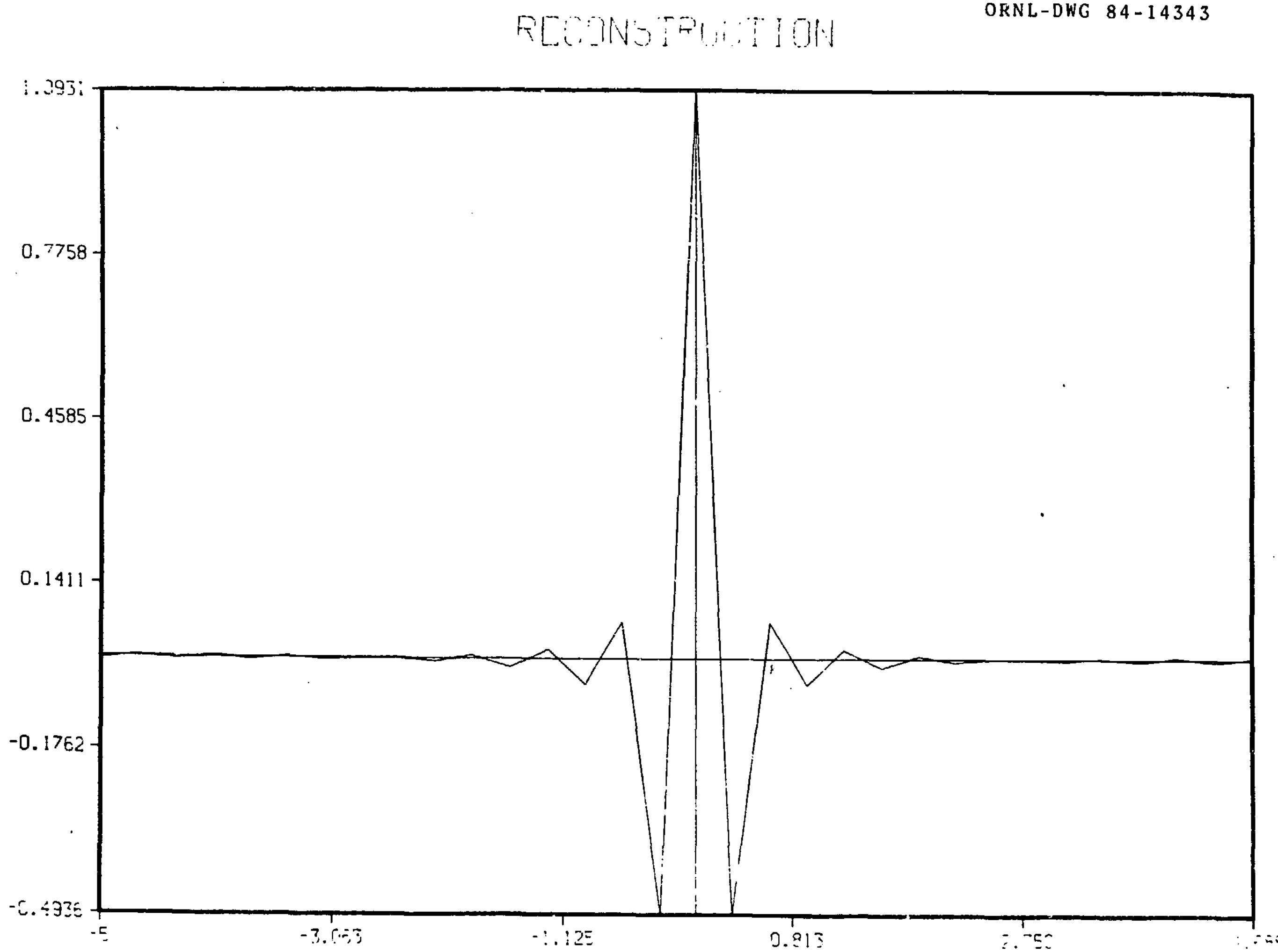


ORNL-DWG 84-14344

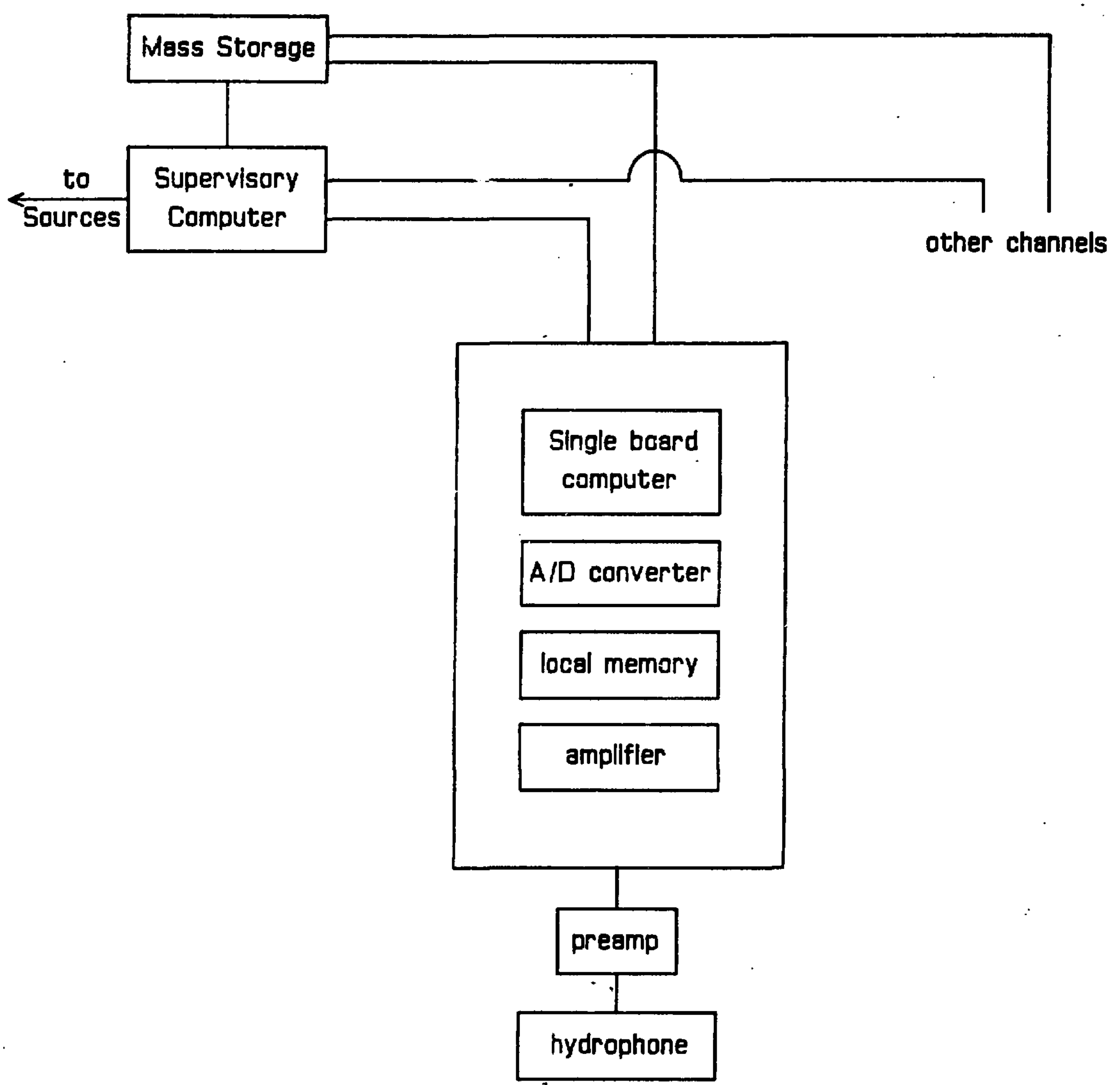
RECONSTRUCTION



ORNL-DWG 84-14343



ORNL-DWG 84-14332



ORNL-DWG 84-7610