Fourth Quarterly Report
to
Electric Power Research Institute, Inc. and KUERP

for

FEASIBILITY OF GROUND-PENETRATING RADAR FOR USE AT MGP SITES

Pawan Chaturvedi, Richard G. Plumb, and Kenneth R. Demarest

Radar Systems and Remote Sensing Laboratory
Department of Electrical Engineering and Computer Science, University of Kansas
2291 Irving Hill Road, Lawrence, Kansas 66045-2969
TEL: 913/864-4835 * FAX: 913/864-7789 * OMNET: KANSAS.U.RSL

RSL Technical Report 9990-4

November 1993

Sponsored by:

Electric Power Research Institute
P. O. Box 10412, Palo Alto CA 94303

and

KUERP
700 SW Harrison, Suite 1430, Topeka KS 66601

Agreement RP2879-27

"DISCLOSURE"

This report has not been reviewed to determine whether it contains patentable subject matter, nor has the accuracy of its information or conclusions been evaluated. Accordingly, the report is not considered a published report and is not available for general distribution, and its distribution is limited to employees and advisors of EPRI for the sole purpose of evaluating the progress and the future course of the project described in the report. Until the report has been reviewed and evaluated by EPRI, it should be neither disclosed to others nor reproduced, wholly or partially, without written consent of EPRI.

The University of Kansas, Center for Research Inc.

Table of Content

I. Summary

This is the fourth quarterly report for the research project, "Feasibility of Ground Penetrating Radar for Use at MGP Sites," EPRI Agreement RP2879-27. This report covers the period from July 1, 1993 through September 30, 1993.

The basic goal of this project is to investigate the feasibility of using a ground-penetrating radar (GPR) for detecting subsurface contaminants. The conventional GPR techniques are mainly concerned with the detection of certain materials in the region being investigated, and not in actually imaging the region. For applications like subsurface contaminant-detection, it is desirable to be able to not only detect the spill, but also determine the extent and the direction of flow of the contaminant. Towards this goal, an imaging scheme is being developed that is capable of imaging contaminants by taking some electric or magnetic field measurements around the object. In the absence of such a scheme, ground samples have to be dug up and analyzed for the presence of any contaminants that may be present. This technique is obviously time-consuming and expensive. Furthermore, several holes have to be dug up around the object to determine the location, the extent, and the direction of the spill. The need for taking multiple core samples and analyzing them would be eliminated if a technique could be developed to image underground objects.

With the primary goal of developing such an imaging scheme, a preliminary survey of the current literature was performed in the first quarter of the project. Diffraction tomography was identified as a possible candidate for this application. This technique is similar to the X-ray tomography used in many medical imaging applications, with suitable modifications made to account for the diffraction effects due to the use of lower frequencies. X-rays cannot be used for subsurface imaging applications because of the higher attenuation suffered by high frequencies while propagating in ground.

In the second quarter of the project, an algorithm was identified to implement the diffraction tomography technique, and it was implemented in a computer program using Matlab software. The results for some simple shapes of the object were presented. It was observed that this technique does not work well with strongly scattering objects since a linear weak scattering approximation is used in this technique to simplify the scattered field equation. Since both weak and strong scatterers might be encountered in an application such as subsurface imaging, a strong-scatterer imaging algorithm was sought.

In the third quarter of the project, an imaging scheme based on iteratively solving for the object profile was investigated. The Born iterative method is one such technique. In this technique, an initial estimate of the object profile is made based on a linear weak scattering approximation, and this object profile is updated at successive iterations so that the error between the measured fields from the actual profile and the fields due to the predicted profile decreases at each successive step. This process of updating the object profile is continued until an acceptable accuracy in the object profile is achieved.

In this report, some results are presented for reconstructions with Born iterative technique for different object properties. Several simulations were done in the last quarter to study the performance of this technique for reconstructing the object profile. Some modifications were made in the Finite-Difference Time-Domain (FDTD) code used for the forward solution required for this technique to make the results more accurate. The FDTD code was also modified to directly give the frequency component used by the imaging program. This results in substantial memory savings.

Most of the programs required for this investigation have been coded in the past quarters of this project. In the next phase of the project, a number of simulations will be performed with more realistic soil and contaminant conditions to determine the viability of the proposed imaging technique. A coal tar sample was received from Atlantic Environmental Services, Inc. and its properties would be incorporated into future simulations.

Modifications are required in the FDTD code to accurately handle a half space that includes the air-ground interface. This provides a complicated electromagnetic problem since the absorbing boundary conditions used at the outer boundary of the grid are not capable of handling such a case. These boundary conditions are required to prevent reflections from the points in space where the FDTD grid used for modeling the region of interest is terminated.

The imaging scheme is proposed to be enhanced by creating a database of several known objects, and using neural networks for the classification of objects. The images obtianed with the imaging technique would not be perfect reconstructions of the objects being imaged. Furthermore, due to the larger wavelengths used for imaging, the finer features of the objects may be lost in the reconstructed images. Use of a neural networks would provide a robust way of identifying and classifying objects being imaged.

II. Introduction

Diffraction tomography is an extension of the X-ray tomography used in many medical imaging applications that takes the diffraction effects into account. Since diffraction tomography is based on a linear solution to the inverse scattering problem, it works well for imaging weakly scattering objects. When multiple targets are present, the weak scattering approximations break down and diffraction tomography technique will no longer give accurate images.

The limitations of diffraction tomography technique were identified in the previous reports. Diffraction tomography linearizes the inverse scattering problem to generate an image. Linearizing the inverse scattering problem is valid only under weakly scattering conditions. Not all contamination sites will fit the weakly scattering model. Therefore, nonlinear techniques of generating images were investigated. The Born iterative method [1] was identified as one such technique suitable for use with ground-penetrating radars.

In the Born iterative method, a linear approximation, based on a weak scattering approximation similar to the one used in diffraction tomography, is used to generate an initial guess of the object profile. In generating the initial profile, the scattered fields are neglected inside the object. This first guess is updated by using the scattered fields predicted by the initial estimate of the object, while computing the total fields inside the object. The scattered fields due to this updated profile at the receiver locations are compared against the measured fields from the actual object. If their difference is within an acceptable error level, the process is stopped; otherwise the total fields inside the object are updated with the new estimate of the object. This iterative process is continued until the error between the measured scattered fields and the fields predicted by the estimated object profile is within an acceptable accuracy level. This iterative technique is a nonlinear technique of solving the image reconstruction problem, and is more robust than diffraction tomography.

With the Born iterative technique, the inverse-scattering problem is solved as a constrained minimization problem in which the error between the measured fields and the predicted fields is minimized at each iteration, subject to a smoothing constraint placed on the object profile. This constraint is required because solutions to inverse problems are not unique. By constraining the problem, a unique solution can be identified. Since in many practical situations, the object profile would be a gradually varying function in space, the smoothness requirement provides a reasonable constraint for many realistic examples.

In the last quarterly report, the theory behind the iterative techniques was outlined, and an algorithm was presented to implement the Born iterative method. This algorithm can be used for any arbitrary transmitter-receiver setup. In place of the plane wave model used in diffraction tomography, line sources can be used with this technique to make the modelling of actual sources easier. In the fourth quarter of the project, the Born iterative method was implemented for both the full-view and the limited-view transmitter-receiver geometries. Simulations were done with a wide range of object contrasts to study the behavior of this technique for different object preperties.

In this report, the results for some numerical examples are presented. Good quality reconstructions are obtained for a wide range of object contrasts. These results demonstrate the usefulness of this technique in dealing with a wide range of object contrasts. Due to the constraint that the object profile is smooth, the images obtained are a smoothed version of the original object. Simulations were done with two different sets of constraints; one, that the object profile itself is smooth, and two, that the first derivative of the object profile in both the horizontal and the vertical direction are smooth. Similar results are achieved for both type of constraints.

In the next section, the results from simulations done with the Born iteretive method are presented for the offset-VSP configuration of the transmitters and the receivers. Some modifications that were done on the FDTD code that is used as a forward scattering solver are mentioed in the fourth section. The scheme proposed to be used for the classification of the objects is presented in the fifth section. Neural Networks are proposed to be used for the classification of the targets. A large database of the known targets would be built for training the neural networks. In the last section, the conclusions from the work in the last quarter and the proposed work for the remainder of the project are presented.

III. Simulations and Results

Simulations were performed for a number of different object contrasts and transmitter-receiver setups. The Born iterative method was used to reconstruct the object profile. Offset-VSP simulations were carried out with 3 line-sources and 17 receivers. The transmitters were placed on the surface, and the receivers were placed in a vertical borehole close to the object. The object space was divided into a uniform grid of 8 cells by 8 cells. Thus, there were 64 unknowns in the problem.

The test objects used for the simulations are shown in Fig. 1, 3, and 5. The peak contrast in the object was varied from 2:1 to 10:1. The results for offset-VSP configuration are shown in Fig. 2, 4, and 6. From the results of the simulations, it is seen that reconstructions of good quality are acheived for a wide range of object contrasts. This is a consequence of using a nonlinear technique for solving the inverse scattering problem. A small object space was used in the simulations to save computational time and memory.

It is seen from the reconstructions that the image obtained is a smoothed version of the original object. This is due to the fact that while solving for the object profile, the smoothness constraint is imposed on the object to select one out of the infinite number of objects that could result in the same fields at the receivers. Simulations were performed with the smoothness constraint applied to the object profile itself, and when this constraint is applied to the first derivative of the object profile in the horizontal and vertical directions. For the smoothness constraint applied to the derivatives, finite-difference approximations of the derivatives were used. Very similar results were obtained with the two sets of constraints. It should be mentioned here that any other suitable constraint could be imposed on the object profile based on the a priori knowledge about the object.

Unilke the full-view case, where the field measurements are available full 360 degrees around the object, for the offset-VSP geometry, the scattered fields are available only in a small range of angles around the object. This results in less information being available about the object for the offset-VSP configuration. For application of this technique to subsurface imaging, a full view of the object would obviously not be possible. Although the limited angular coverage limits the information available about the object, the results from these simulations indicate that by using an offset-VSP setup, images of sufficiently good quality can be achieved even in the absence of a full view of the object. The reconstruction of the object shown in Fig. 5 indicates that this technique also works well for long, thin objects.

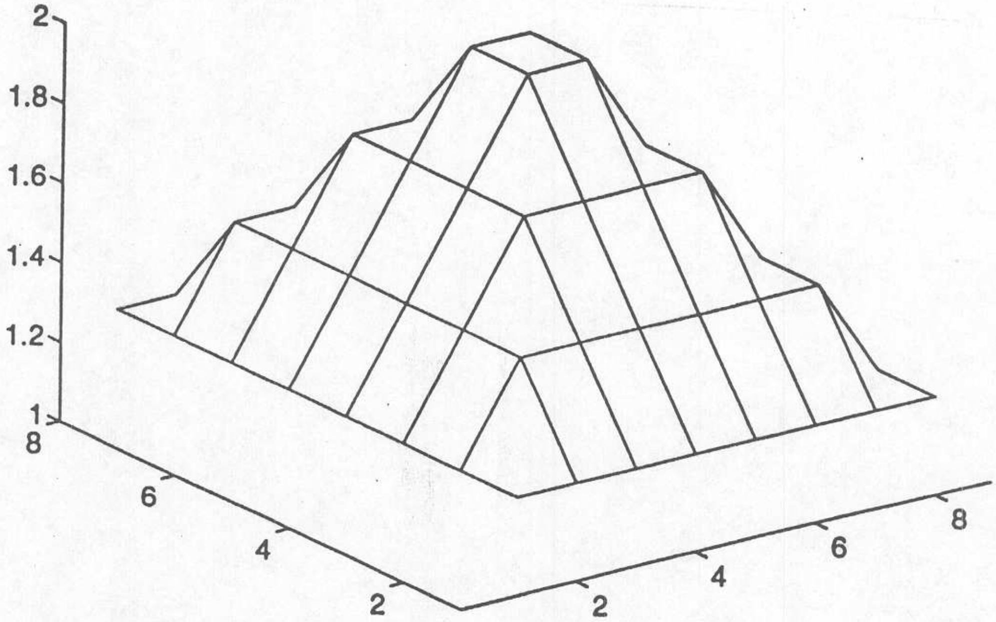

Fig. 1. Test object with a peak contrast of 2:1.

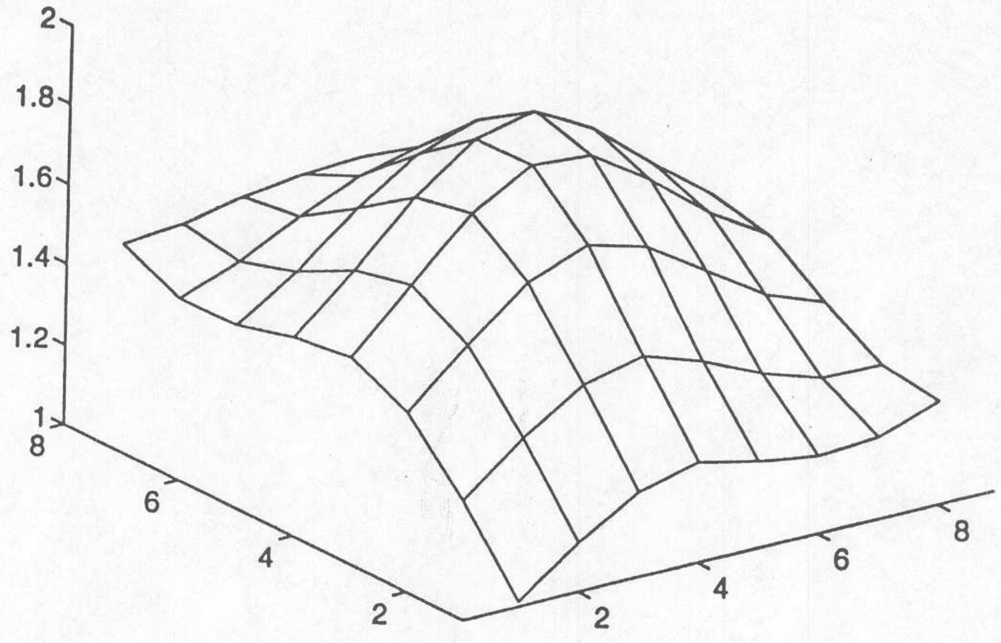

Fig. 2. Reconstruction with offset-VSP for the object shown in Fig. 1.

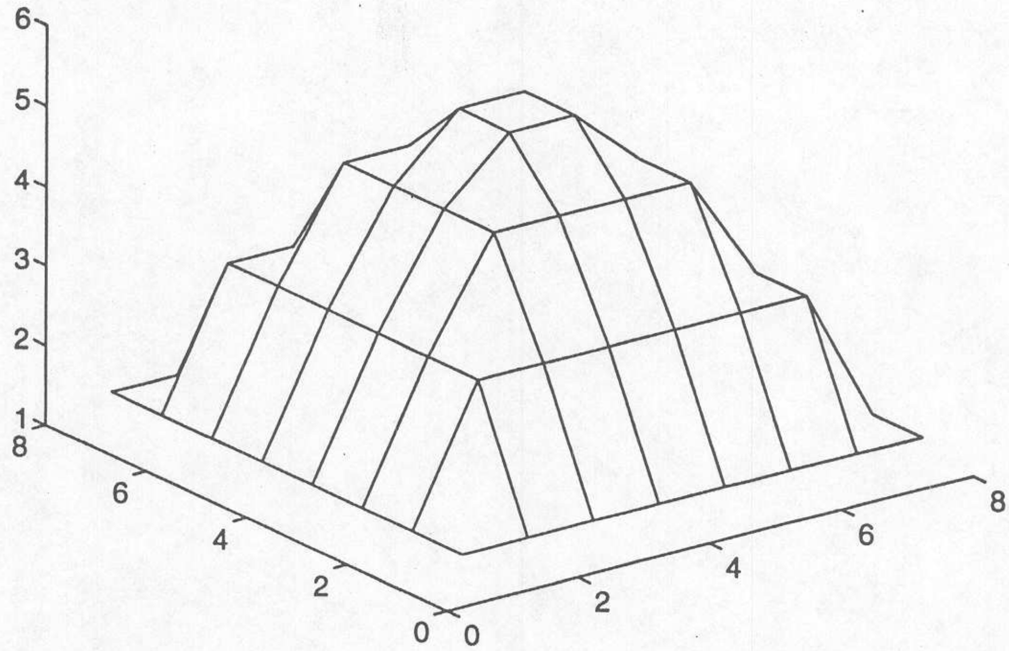

Fig. 3. Test object with a peak constrast of 6:1.

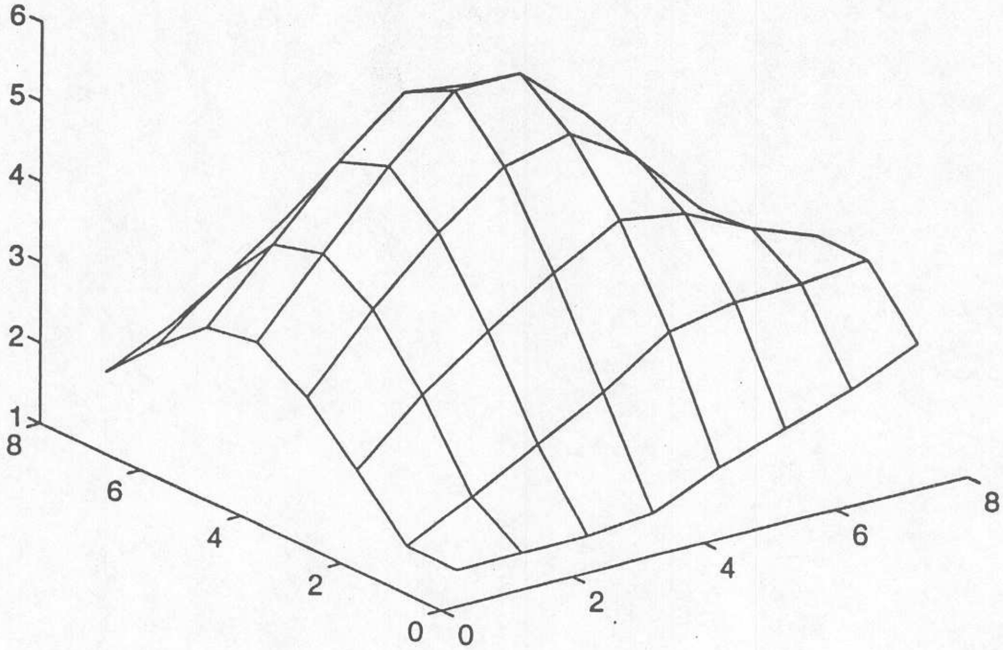

Fig. 4. Reconstruction with offset-VSP for the object shown in Fig. 3.

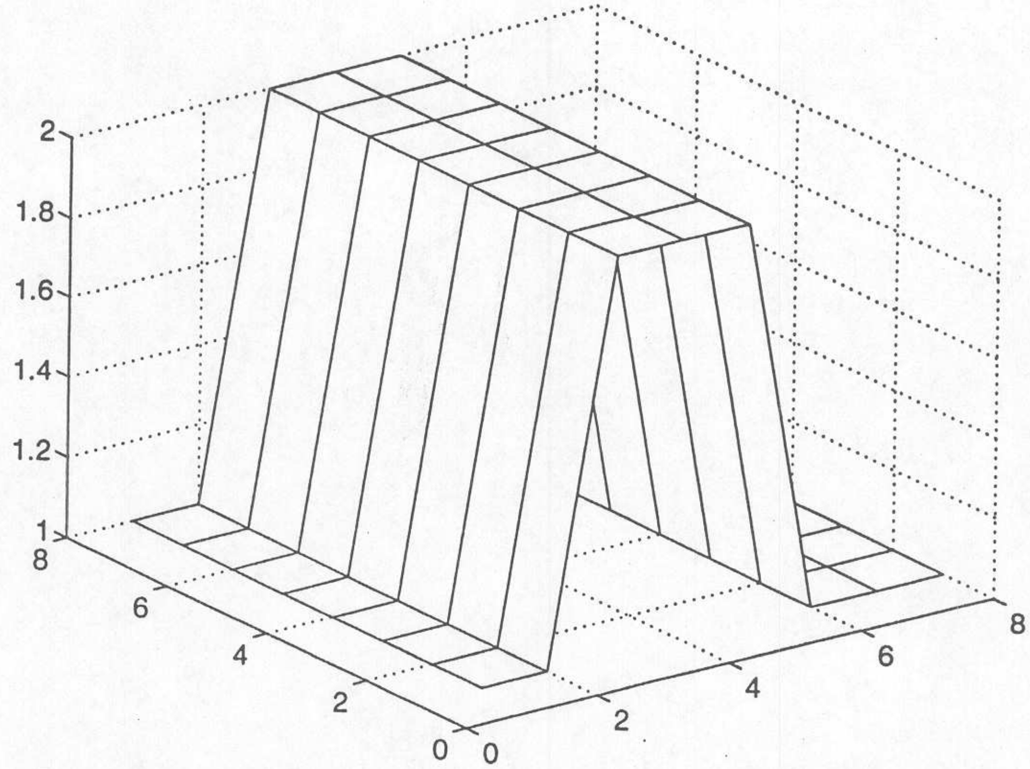

Fig. 5. A long, thin test object with a peak contrast of 2:1.

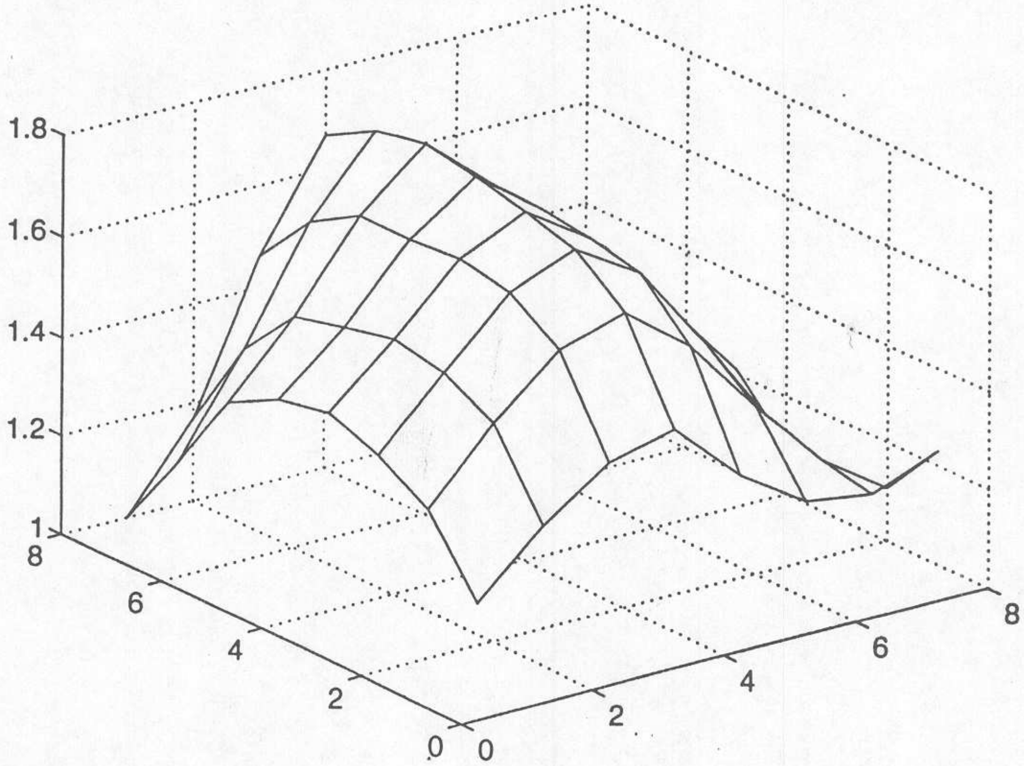

Fig. 6. Reconstruction with offset-VSP for the object shown in Fig. 5.

IV. Forward Scattering Solution

To solve the image reconstruction problem as outlined in the previous sections of this report, a forward solver is required to evaluate the scattered fields from the actual object and the estimated object profile. Finite-Difference Time-Domain (FDTD) technique is being used for this project to solve the forward scattering part of the problem. This technique provides a numerical method for propagating the electromagnetic fields in space modelled by a finite-difference grid. The basic concept of this technique was described briefly in the last report, and several good references are available for a detailed description of this technique.

The space in which the electromagnetic waves are to propagate is divided into a cartesian grid, or lattice. Each cell in the grid is 0.2 m by 0.2 m in dimensions. The modelled space covers all the transmitter and receiver locations, and the object being imaged. The object is 8 cells long and 8 cells wide. For the simulations done for this work, only the 80 MHz component of the signal is being used.

The FDTD code outputs the electromagnetic fields as a function of time. The time-domain data can be used to compute the fields at several frequencies. Since most of these frequencies are not used in the reconstruction process, saving the entire time-domain data is unnecessary. The FDTD code was modified to compute the desired frequency component online, and to save only this single frequency component. This method of computing the fields results in significant savings in the memory required for running the code, and also cuts down the post-processing of the data. Transfer and processing of the large amounts of time-domain data to extract a single frequency component is no longer required.

The FDTD code was written in the Frotran programming language, and the inverse scattering program used for imaging has been written in Matlab software. To link the two programs so that the data can be transferred from one program to the other, a software interface was also built. This interface program loads and saves the data at the desired location in the required format.

A basic difficulty in applying FDTD to scattering problems is that the domain in which the fields are to be computed is open or unbounded. Since computers have finite memory, the FDTD lattice must be terminated and an artificial boundary must be imposed around the scatterers. The purpose of the artifcial (or absorbing) boundary condition is to create the numerical illusion of an infinite space. A number of good absorbing boundary conditions are available and all assume that the scatterer can be confined inside the lattice. Since no absorbing boundary condition is perfect, waves are reflected from the outer boundary. Good absorbing boundary conditions provide roughly 40 dB of attenuation. In other words, the reflected wave is 40 dB down from the wave incident upon the boundary.

The basic problem associated with applying FDTD to simulate GPR data is the absorbing boundary condition. In GPR work, the soil itself is a scatterer, and extends all the way out to the artificial boundary. Therefore the existing absorbing boundary conditions must be modified to accurately handle the half-space interface encountered in GPR modeling. If no modifications are made, the reflected wave off the absorbing boundary may only be 10 dB down from the incident wave. The resulting surface wave coming back from the outer boundary would be very large, greatly limiting the simulations. We, therefore, are looking at ways to modify the FDTD code to handle the air-soil interface.

V. Object Classification

It is seen from the reconstructed images that fairly good quality reconstructions are achieved for a wide range of object contrasts with the Born iterative method. Despite the good quality of the images, some of the finer details of the objects are lost in the reconstruction process. In applying the constraints to the object profile, the only requirement that is imposed is that the profile be smooth. There is no information used in the reconstruction process that uses any information about the actual shape of the object. If there is any a priori information available about the actual shape of the object, it could be used for the classification of the targets.

In the imaging of subsurface spills, some information is usually available about the shape of the object being imaged. In many situations, the shape of the plume formed by the contaminant would also form a known shape. The properties of the soil and the contaminant were briefly described in the last report. The investigation of the contaminant profiles [2] has been reported to show that the contaminants are known to form plumes of different shapes under different surroundings. This data, combined with the known shapes of the containers, can be used to form a database of the known targets expected to be encountered in such an application. This database can be used to train neural networks for classifying the images obtained with the imaging scheme [3].

The neural networks would be trained with the noisy images of the known targets, and this information would be stored in a database. These networks can then be used to classify the images obtained with the object reconstruction technique developed for this project. It is expected that this scheme would provide a very robust and powerful technique for classifying the images by combining the signal processing techniques with the image processing and electromagnetic techniques currently being used.

VI. Conclusions and Future Work

Two different types of imaging schemes were investigated in the last three quarters of the project. The diffraction tomography technique uses a weak-scattering approximation to linearize the object reconstruction process. This technique, although conceptually simple, fails for many objects that do not satisfy the weak-scattering approximation. In the past quarter of the project, a nonlinear imaging scheme based on iteratively solving for the object profile was developed. This technique works well for a wider range of object profile contrast, and does not require the object to satisfy the weak-scattering approximation. Some of the results obtained with this technique were presented earlier in this report.

The FDTD code was modified to make it suitable for the present application. Work is currently under way to develop the appropriate boundary conditions required by FDTD technique to handle the air-soil interface.

A major part of the codes required for the testing of the imaging scheme has already been developed in the last four quarters of this project. In the remaining time for this project, the imaging scheme will be tested using realistic simulations, and the performance of the imaging technique will be evaluated. The generated images will then be classified using neural netwroks.

It is expected that the imaging techniques, combined with the classification algorithms, will provide a very robust, comprehensive, and powerful approach to detect, image, and classify subsurface contaminants.

VII. References

[1] Wang, Y.M., and Chew, W.C., "An Iterative Solution of the Two-Dimensional Electromagnetic Inverse Scattering Problem," Int. J. of Imaging Syst. and Tech., vol. 1, pp. 100-108, 1989.

[2] Douglas, D.G., Burns, A.A., Rino, C.L., and Maresca, J.W., Jr., "A Study to Determine the Feasibility of Using a Ground-Penetrating Radar for More Effective Remediation of Subsurface Contamination," Tech. Report EPA/600/R-92/089, U.S. Environmental Protection Agency, 1992.

[3] Chaturvedi, P., and Plumb, R.G., "Subsurface Imaging Using Higher Order Inversion Techniques," Second Government Workshop on GPR - Advanced Ground Penetrating Radar: Technologies and Applications, Columbus, Ohio, Oct. 26-28, 1993.

Fourth Quarterly Report to

Electric Power Research Institute, Inc.

Att: Dr. Jerry Lonergan, Director
KEURP
400 S.W. 8th. - Suite 314
P. O. Box 1007
Topeka, KS 66601-1007

for

Feasibility of Ground Penetrating Radar for Use at MGP Sites

Pawan Chaturvedi, Graduate Research Assistant

Richard G. Plumb, Assistant Professor
Principal Investigator

Ken R. Demarest, Associate Professor
Co-Investigator

Electrical and Computer Engineering
The University of Kansas Center for Research, Inc.

November 5 1993