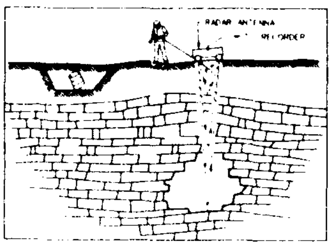
US Army Corps
of Engineers



GEOTECHNICAL LABORATORY

MISCELLANEOUS PAPER GL-92-40

PROCEEDINGS OF THE GOVERNMENT USERS WORKSHOP ON GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT 26–27 MARCH 1992 VICKSBURG, MISSISSIPPI

Compiled by

Dwain K. Butler

Geotechnical Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
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US ARMY ENGINEER WATERWAYS EXPERIMENT STATION

December 1992
Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1992	Final report

4. TITLE AND SUBTITLE
Proceedings of the Government Users Workshop on Ground Penetrating Radar Applications and Equipment

5. FUNDING NUMBERS
See reverse.

6. AUTHOR(S)
Compiled by Dwain K. Butler

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
Miscellaneous Paper GL-92-40

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
This report is available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The first Government Users Workshop on Ground Penetration Radar (GPR) Applications and Equipment attracted 60 attendees from 17 government agencies/offices and private industry. Presentations emphasized the wide variety of applications of CPR and current and emerging technology in GPR equipment. The workshop included field demonstrations at the Waterways Experiment Station Environmental Geophysics Training Facility. A concluding panel discussion summarized the highlights of the workshop and discussed research and development needs and requirements.

14. SUBJECT TERMS

Antennas	GPR	Radar
Geophysics	Ground penetrating	

15. NUMBER OF PAGES
96

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

5. Continued.

Project AT40, Task WS,
Work Unit 001,

REMR Research
Work Unit No. 32638

PREFACE

A Government Users Workshop on Ground Penetrating Radar Applications and Equipment was held at the US Army Engineer Waterways Experiment Station (WES) on 26-27 March 1992. The Workshop was sponsored by the Headquarters, US Army Corps of Engineers, under the RDTE Program, Project AT40, Task WS, Work Unit 001, "Subsurface Water Location," and the Repair, Evaluation, Maintenance and Rehabilitation (REMR) Research Project "Non-Destructive Evaluation Systems for Civil Works Structures," Work Unit No. 32638.

The Workshop was organized and coordinated by Dr. Dwain K. Butler, Earthquake Engineering and Geosciences Division (EEGD), Geotechnical Laboratory, WES, with the assistance of an Organizing Committee. Mr. Michael K. Sharp, EEGD, a member of the Organizing Committee, played a key role prior to and during the Workshop, serving as overall Workshop Moderator. This report on the proceedings was compiled and prepared by Dr. Butler.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

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GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT
26-27 March 1992

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GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT
26-27 March 1992

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GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT

26-17 March 1992

AGENDA

Thursday, 26 March
Introduction

0800 Registration

0830 Welcome--Paul F. Hadala, Assistant Chief, Geotechnical Laboratory, US Army Engineer Waterways Experiment Station

0840 Organizational Details and Arrangements--Michael K. Sharp, US Army Engineer Waterways Experiment Station

0850 "Elementary GPR Overview and Workshop Scope"--Dwain K. Butler, US Army Engineer Waterways Experiment Station

0920 "Overview of Key Geologic Factors Effecting GPR Performance"--Richard D. Lewis, US Army Engineer Waterways Experiment Station

Case Histories/Applications

1000 "Testing for Unmarked Graves"--Bruce W. Bevan, Geosight

1020 "Fracture and Cavity Detection and Mapping with GPR: An Overview with Examples"--R.C. Benson and Lynn Yuhr*, Technos Inc.

1040 "Application of GPR for Location of Old Mine Workings" --J.E. Scaife, P. Giamou, and A.P. Annan*, Systems and Software, Inc.

1100 "The Detection and Location of Abandoned Gas Wells in Coal Seams by GPR"--Robert C. Kemerait, ENSCO, Inc.

1120 "Applications of GPR in the Georgia Coastal Plains"-- C.C. Truman* and D.D. Bosch, Department of Agriculture, Agricultural Research Service

* Presenter

1140 "Role of GPR in Integrated Geophysics Assessments"--D.K. Butler* and M.K. Sharp, US Army Engineer Waterways Experiment Station

1330 "Use of Ground-Penetrating Radar in Hydrologic, Bridge Scour, and Fracture Studies"--J.W. Lane*, F.P. Haeni, and Gary Placzek, Water Resources Division, US Geological Survey

1350 "Application of GPR to Contaminated Ground Water Mapping"--A.P. Annan*, J.D. Redman, and S.W. Conway, Systems and Software, Inc.

1410 "Advances in GPR for Pavement Research"--Stan Smith, Geophysical Survey Systems, Inc.

1430 "Use of GPR Within the USDA-Soil Conservation Service"--James Doolittle, Department of Agriculture, Soil Conservation Service

1510 "A FM-CW Radar Used for Probing of Brick Structures"--Oren Tranbarger* and Bob Duff, Southwest Research Inst.

<u>New Initiatives</u>

1530 "Application of Maximum Entropy to GPR"--Louis Roemer*, David Cowling, and Leo Zou, Louisiana Tech University

1550 "The Use of GPR in Trenchless Excavation"--David Cowling, Louis Roemer*, and Leo Zou, Louisiana Tech

1610 "Problems Encountered and Role for GPR in Concrete Technology and Corps Structures Assessment"--A.M. Alexander, US Army Engineer Waterways Experiment Station

1630 "Initiation of a NDT/GPR Research and Development Effort"--Falih Ahmad, US Army Engineer Waterways Experiment Station

Friday, 27 March

<u>Equipment: Status, New Developments, Considerations</u>

0800 "Recent Advances in Subsurface Interface Radar Technology"--Thomas J. Fenner, Geophysical Survey Systems, Inc.

0830 "An Overview of the pulseEKKO™ GPR Technology"--A.P. Annan* and S.W. Cosway, Systems and Software, Inc.

0900 "Airborne, Borehole and Surface GPR: Measurement, Processing, and Modeling"--Gary R. Olhoeft, Branch of Geophysics, US Geological Survey

1000 FIELD DEMONSTRATIONS

Wrapup

1300 Panel Discussion--Butler, Bevan, Annan, Fenner, Olhoeft, Doolittle

1430 Open Discussion; Synopsis

GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT

INTRODUCTION

Background

Ground penetrating radar (GPR) has emerged as a versatile, high resolution geophysical method for a wide variety of geotechnical (engineering, ground water, archaeology, environmental site characterization) applications. When GPR systems became commercially available in the 1970's, the capabilities of GPR were easily oversold to a market eager for "high-tech solutions" to difficult geotechnical problems. In certain ideal geologic settings and for ideal targets, even the very early GPR systems could produce "real time" reflection records (i.e., no processing required) which resembled snapshots of the subsurface; this capability was easily exploited. This "overselling" led to frequent application of GPR to inappropriate sites and objectives, and GPR use by inexperienced personnel was and continues to be a problem. Fortunately, the capabilities and limitations of GPR are now better understood by geophysicists and the geotechnical community as a whole, and the method is being more rationally exploited.

Commercially available GPR's are short pulse, time domain, electromagnetic (EM), wave propagation systems. The GPR's utilize closely-spaced EM transmitters and receivers, and the GPR graphic data display appears just like a common depth point seismic section. However, when interpreting the GPR section, factors must be considered which are not relevant in seismic reflection: scattering from gravel, cobbles, microcrack clusters, and other small, geologic inhomogeneities; backscatter signatures from overhead powerlines and other surface structures can masquerade as subsurface features in the GPR record; "minor" changes in dielectric properties of soil, rock or water can appear as major GPR signatures but do not affect other physical properties. Advantages of GPR are extremely high vertical and horizontal resolution, rapid survey capability, and near real-time data interpretation in many cases. Major disadvantages or limitations are the extremely site-specific applicability and limited depth of investigation capability (generally less than 15 m).

New digital GPR systems are now available with higher dynamic ranges than the earlier analog GPR systems. The new GPR systems, along with a growing emphasis on GPR data processing and new interpretive procedures, promise increased GPR applicability in the future. Some of the site-specific applicability restrictions may be overcome by improved instrumentation, and overall interpretation will be improved by processing. As with all advances in the state-of-the-art, however, "typical examples" and marketing hype often exceed the real potential by a considerable margin. It is important that government users of GPR remain cognizant of advances in GPR equipment, new and/or improved GPR data processing and interpretation procedures, and new GPR application areas. This workshop was planned to promote technology transfer and interchange among government users of GPR.

Scope

Government GPR users will generally perform one or more of the following functions:

- --Specify or propose applications or GPR
- --Contract for GPR services
- --Monitor and/or review GPR work
- --Conduct GPR surveys
- --Interpret GPR survey results

Clearly the type and depth of knowledge of GPR systems, applications, data processing, and interpretation differ for each of these functions. This workshop was designed to (1) discuss a variety of current applications, (2) discuss limitations and requirements for quality assurance and control, and (3) introduce state-of-the-art and emerging technology in GPR equipment, data processing, and interpretation.

A list of existing and potential areas of government utilization of GPR is presented below (certainly not all-inclusive).

- --Cultural resources management (archaeological applications)
- --Hazardous and toxic waste site characterization
- --Ground water exploration
- --Ground water contaminant plume mapping
- --Organic contaminant detection/characterization
- --Site investigations in karst regions
- --Unexploded ordnance detection and mapping
- --Subsurface mine detection
- --Geotechnical investigations (Dams and dam foundations, pavement evaluation, bridge scour, right of way surveys, etc.)
- --Existing structure assessment
- --Soil stratigraphic studies and mapping
- --Ice and permafrost thickness mapping
- --Waterborne surveying applications
- --Cavity and tunnel detection
- --Borehole Radar; Tomographic data acquisition and processing
- --Airborne radar (large, remote, and/or hazardous area surveying)

The presentations and discussions in the workshop covered many of the above topic areas.

In addition to presentations and discussions, the workshop included field demonstrations and exhibits by two GPR equipment manufacturers and a panel discussion. Two field demonstration sites were utilized: (1) a concrete test section with varying thicknesses of concrete over soil; (2) the WES Environmental Geophysics Training Facility. The training facility presently consists of several buried 55-gallon drums (at different depths and orientations), a sand-filled trench, and a buried pipe. Since many participants had never actually seen a GPR survey performed, the field demonstrations were instructive and well-received. Pictures of the field demonstrations and typical GPR records from the training facility are presented in the Field Demonstrations and Exhibits section. Finally, a synopsis of the concluding Panel Discussion is presented.

GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT

WORKSHOP ABSTRACTS, PAPERS, AND PRESENTATION MATERIALS

The following section consists of material submitted by the workshop presenters and is printed as submitted with no editing. The material ranges from brief abstracts to expanded abstracts to full-length papers to hard copies of visual presentation materials. Although varied in format, the material in this section presents a good summary of the workshop. Following the Abstracts section is a discussion of the exhibits and field demonstrations (beginning on page 78) and a synopsis of the Panel Discussion (beginning on page 90).

ELEMENTARY GPR OVERVIEW

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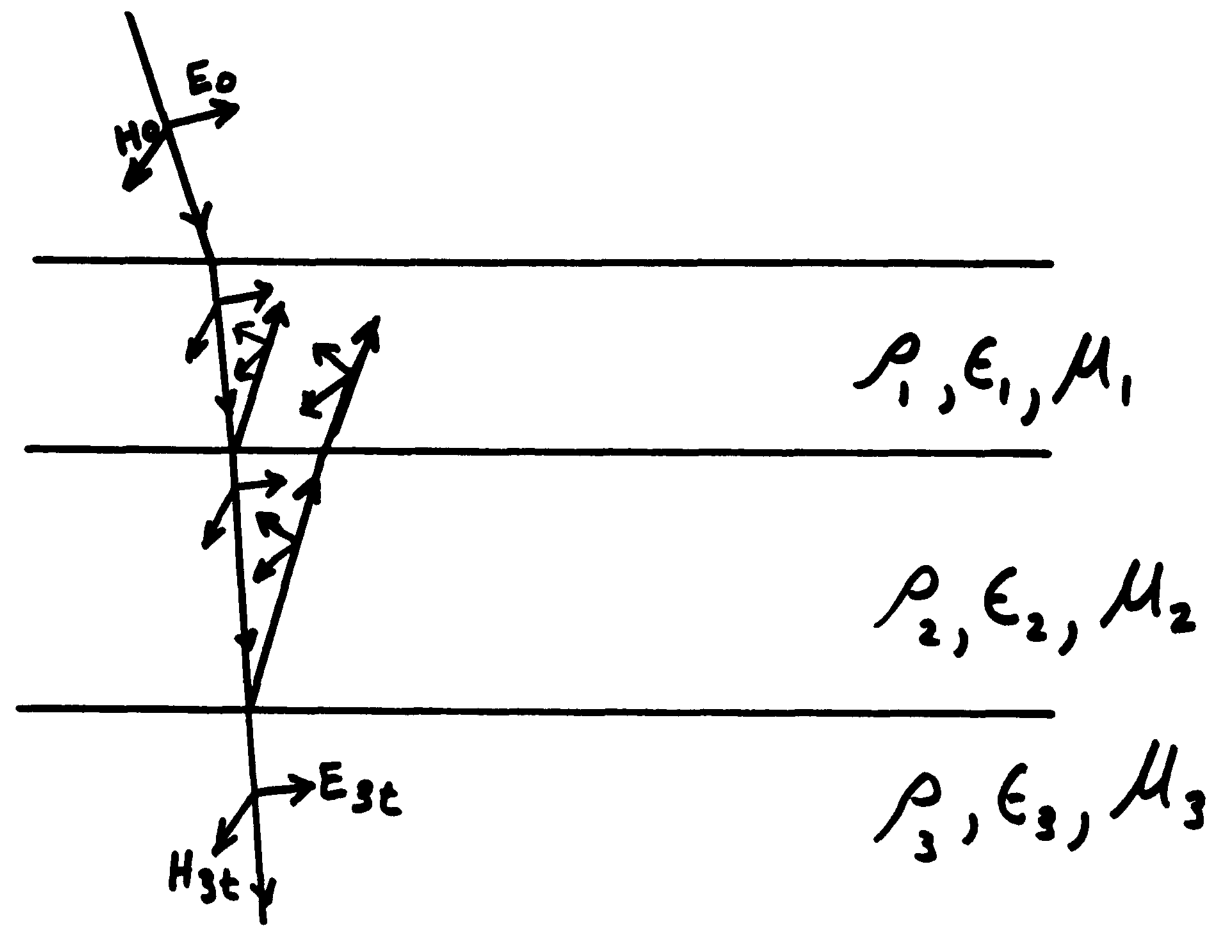
Note: The following pages are reproductions of the visuals used for this tutorial presentation.

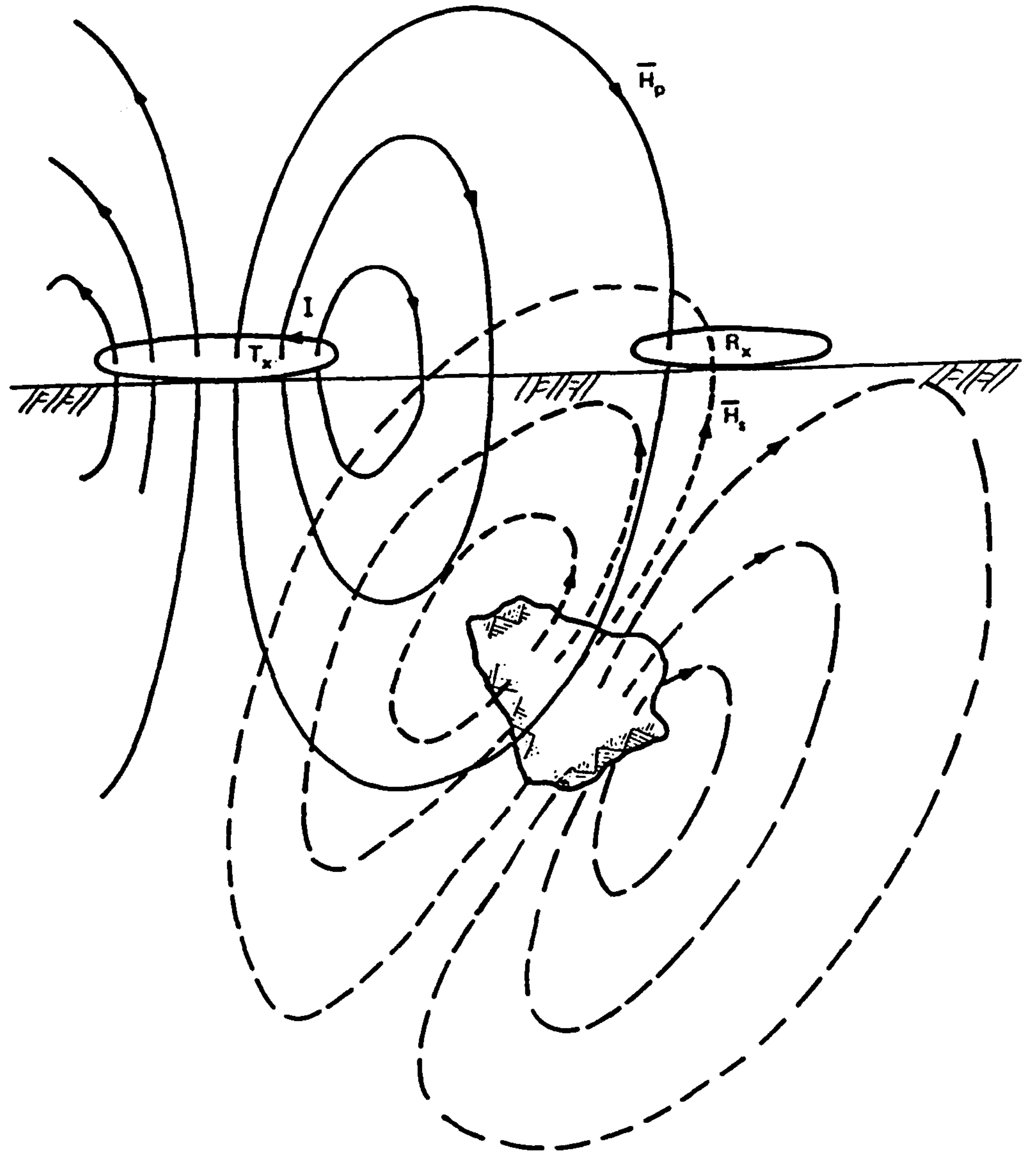
GROUND PENETRATING RADAR (GPR)

- **GPR IS AN ELECTROMAGNETIC METHOD**
  - **PULSE RADARS**
  - **CONTINUOUS WAVE (CW) RADARS**

- ***CONCEPT* - -**
  - TRANSIENT ELECTROMAGNETIC WAVES ARE REFLECTED, REFRACTED, AND DIFFRACTED IN THE SUBSURFACE BY CHANGES IN ELECTRICAL CONDUCTIVITY AND DIELECTRICAL PROPERTIES
  - TRAVEL TIMES AND AMPLITUDES OF REFLECTED, REFRACTED AND DIFFRACTED WAVES CAN BE ANALYZED TO GIVE DEPTHS, GEOMETRY AND MATERIAL TYPE INFORMATION



WAVE PROPAGATION CONCEPTS



CONCEPT OF ELECTROMAGNETIC INDUCTION
IN GEOPHYSICAL EXPLORATION

GROUND PENETRATING RADAR (GPR)

ADVANTAGES - -

- HIGH RESOLUTION, VERTICALLY AND LATERALLY
- RAPID
- COST-EFFECTIVE
- GENERALLY, NEAR REAL TIME INTERPRETATION
- POTENTIAL FOR ORGANIC CONTAMINANT DETECTION
- NUMEROUS AREAS OF APPLICATION

LIMITATIONS - -

- GENERALLY, SHALLOW DEPTH OF INVESTIGATION (< 15 M)
- SITE SPECIFIC APPLICABILITY

GPR CONCEPTS

EM WAVE SPEED, DEPTH OF INVESTIGATION, AND RESOLUTION

WAVE SPEED

$C_s = C_o / \sqrt{k}$

$C_o = 3 \times 10^8$ M/S ; SPEED OF LIGHT IN VACUUM

k = RELATIVE PERMITTIVITY (OFTEN DENOTED AS ϵ_r)

DEPTH OF INVESTIGATION

DEPENDS ON SIGNAL ATTENUATION, WHICH IS A FUNCTION OF ELECTRICAL CONDUCTIVITY, FREQUENCY AND OTHER FACTORS

RESOLUTION

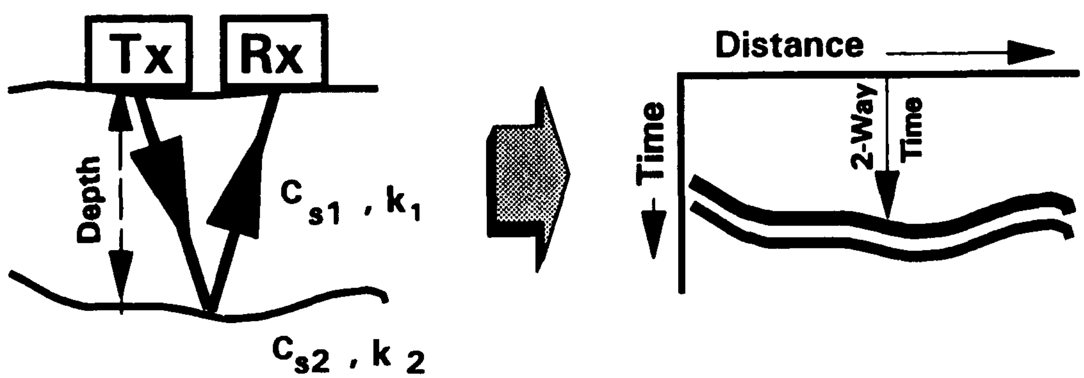
DEPENDS ON EM WAVELENGTH, ANTENNA BANDWIDTH, ANTENNA BEAMWIDTH, ANTENNA PULSE LENGTH

GPR CONCEPTS

- COMMONLY, Tx AND Rx ARE CLOSE TOGETHER, AND THE PATH CAN BE CONSIDERED TO BE VERTICAL
- APPEARANCE AND INTERPRETATION ARE SIMILAR TO A CDP SEISMIC SECTION (RECORD)
- DEPTH = $1/2 \; (C_s \times T_{total})$

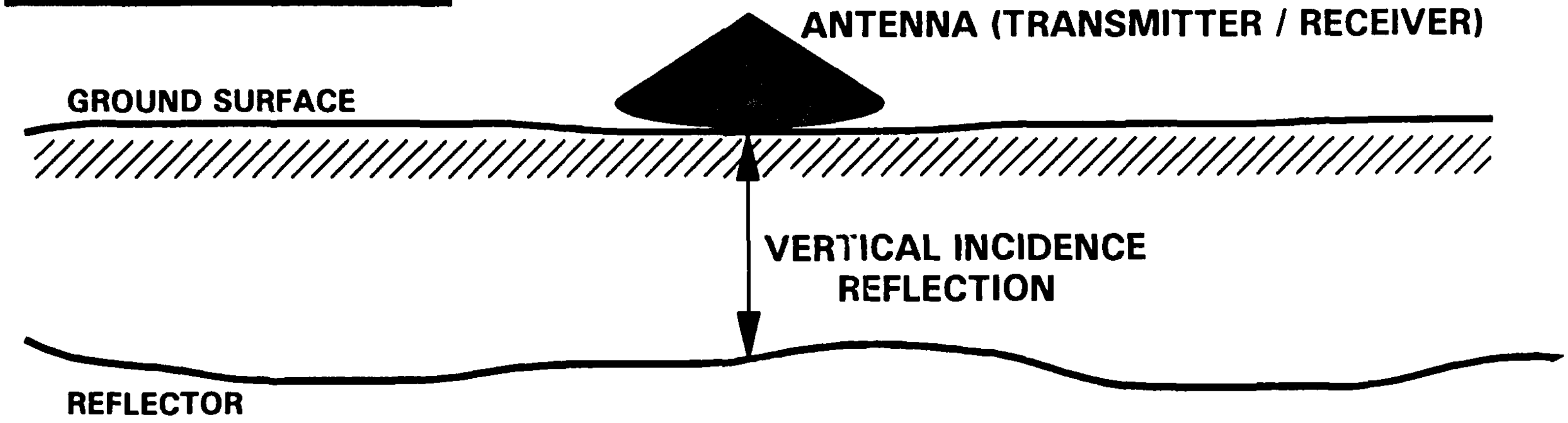
  C_s = SPEED OF EM WAVE PROPOGATION IN SUBSURFACE

$$T_{1\text{-way}} = 1/2 \; T_{total}$$

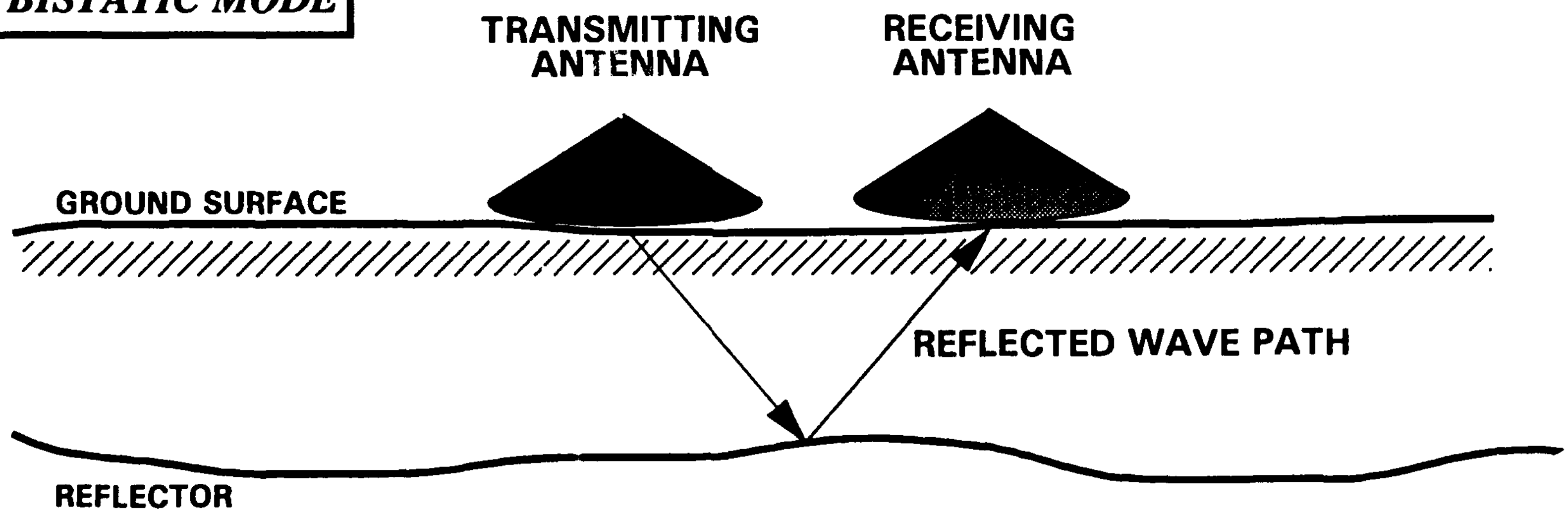


GPR ANTENNA ARRANGEMENTS

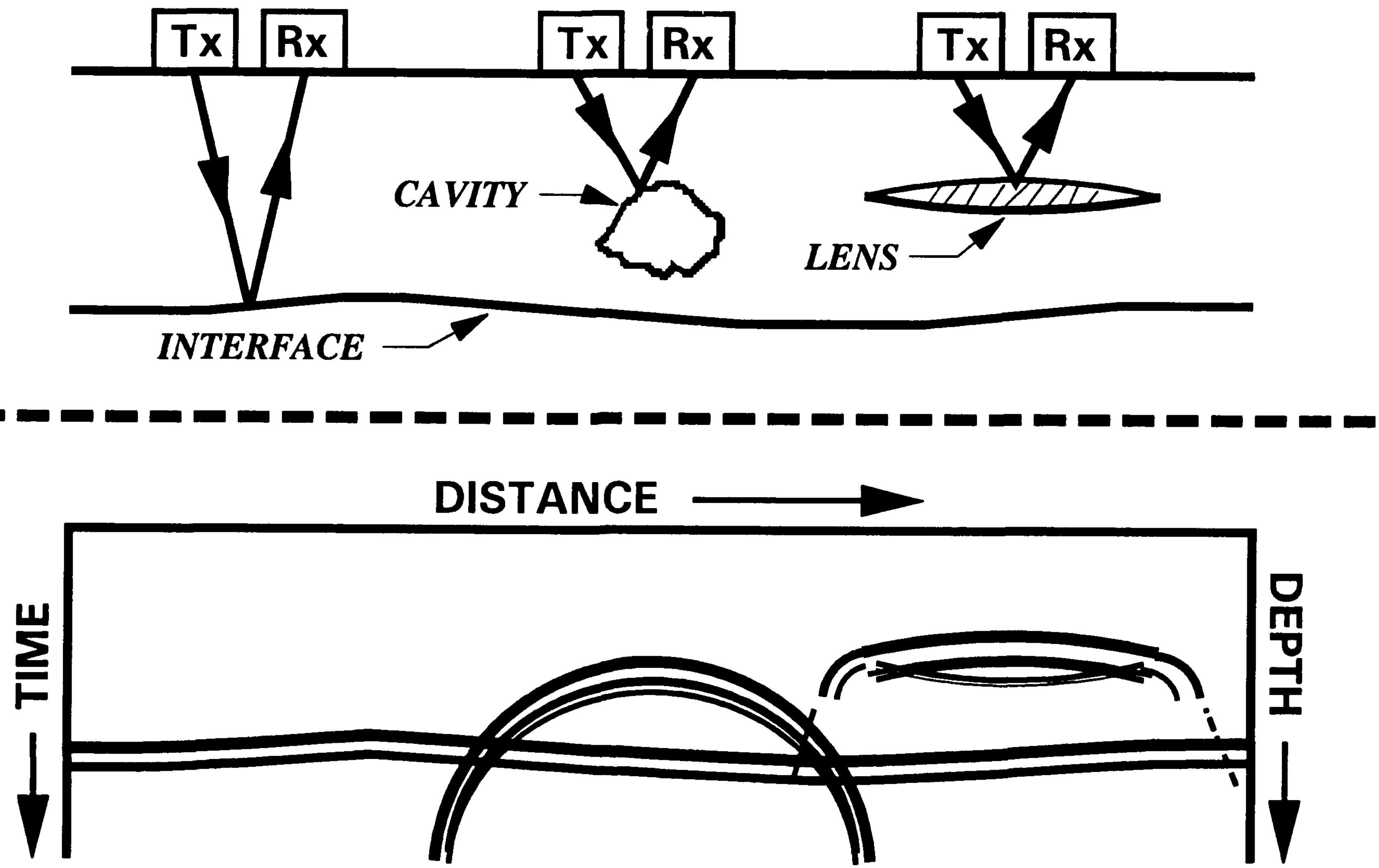
MONOSTATIC MODE



BISTATIC MODE



GPR CONCEPTS



GPR ANTENNA CHARACTERISTICS

DEFINITIONS

CENTER FREQUENCY

Frequency Corresponding to the Peak Power of the Radiated Spectrum

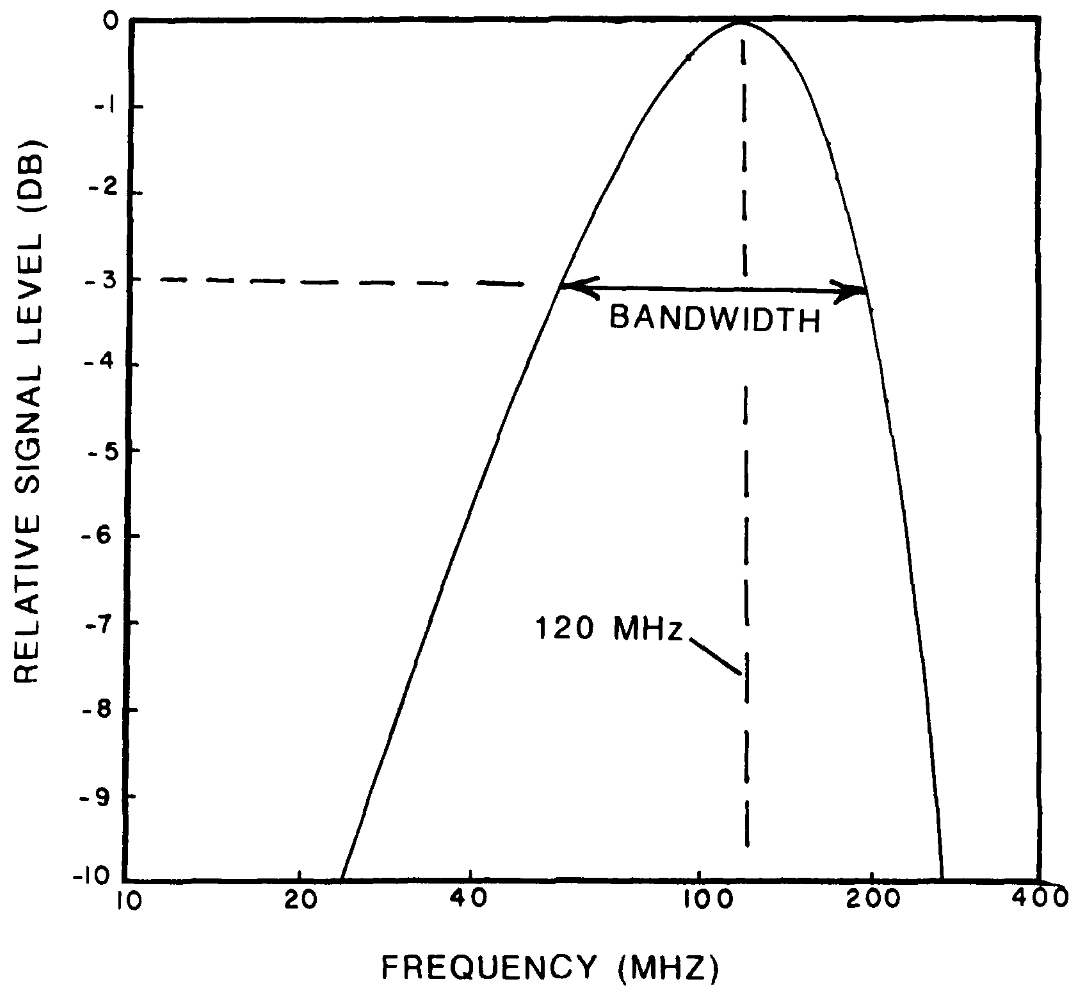
BANDWIDTH

Wideth in Hz Between Two Frequencies at Half-Peak Power (-3dB) of the Radiated Spectrum

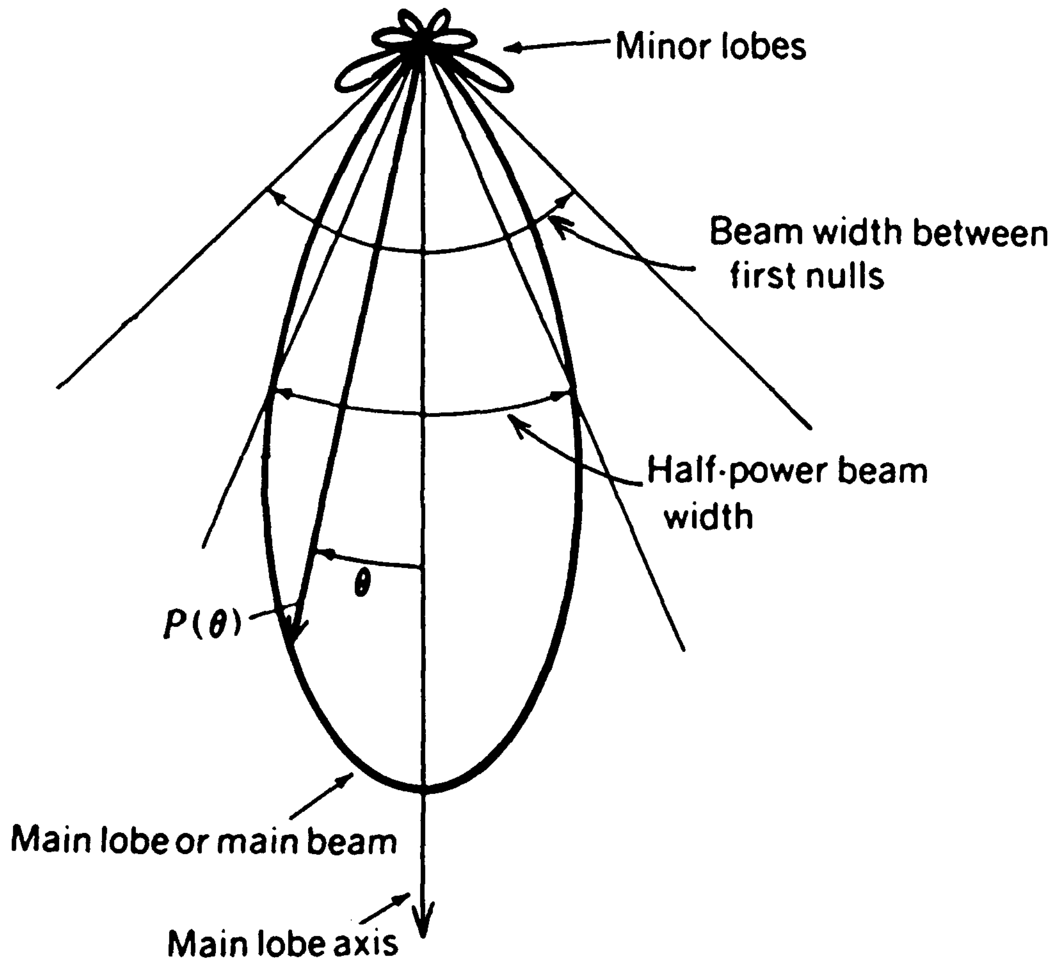
BEAMWIDTH

Angular Width of Main Lobe of the Radiation Pattern

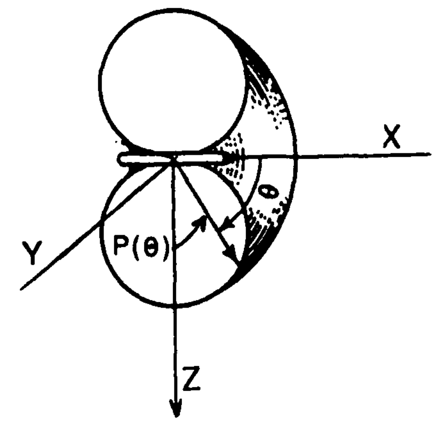
Hypothetical Spectrum for 120 MHz Antenna



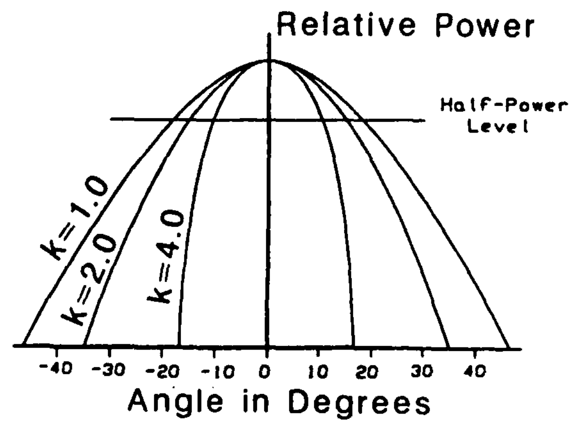
Hypothetical Radiation Patterns



DIRECTIONAL ANTENNA



DIPOLE ANTENNA



EFFECT OF PERMITTIVITY ON RADIATION PATTERN

TRANSITTER FREQUENCIES AND WAVELENGTHS

TYPICAL Tx CENTER FREQUENCY (MHz)	NOMINAL WAVELENGTH* (M)
80	1.9
100	1.5
120	1.3
300	0.5
500	0.3
1000	0.15

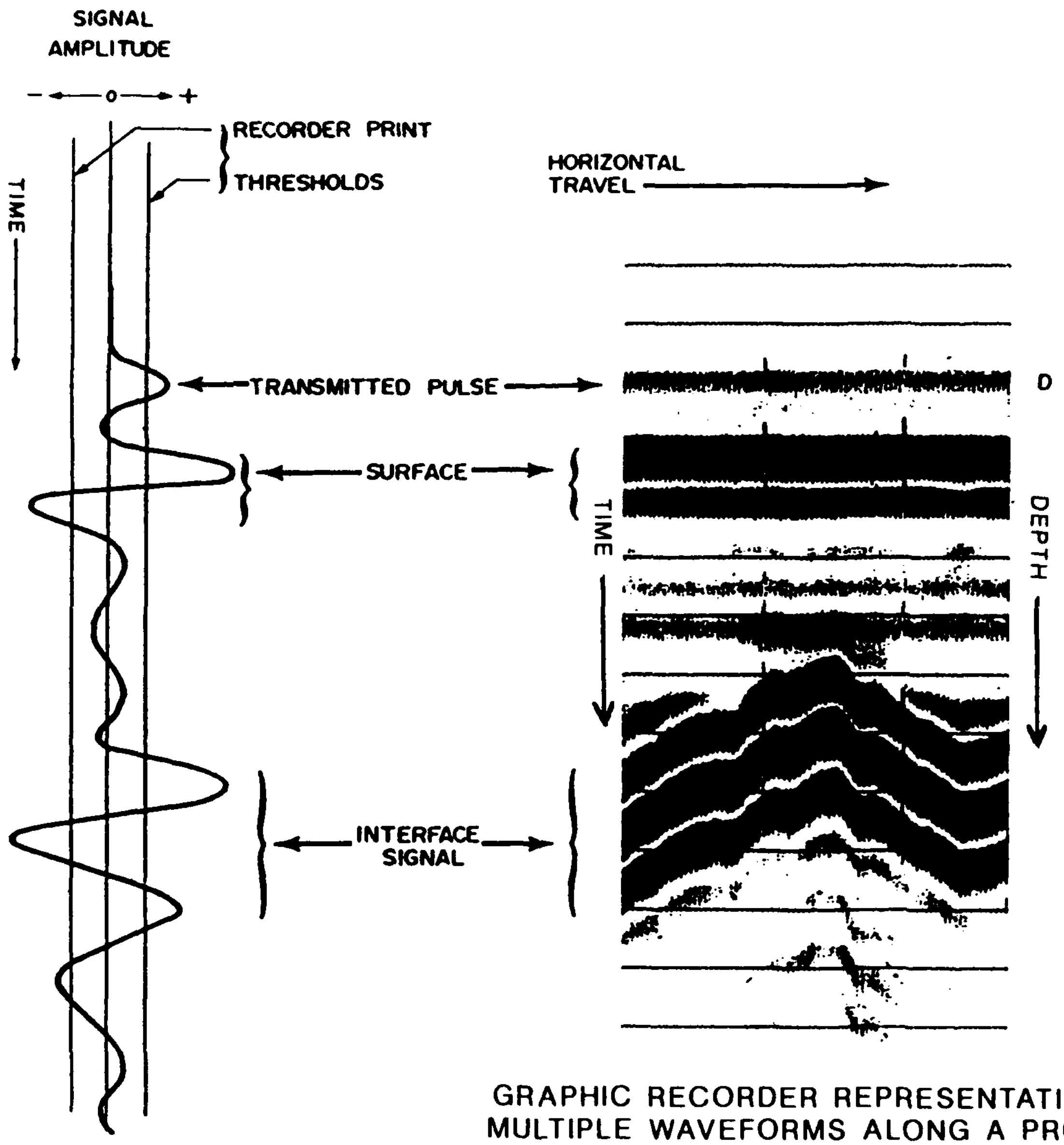
* WAVELENGTH AT CENTER FREQUENCY, ASSUMING k = 4

GPR DEPTH OF INVESTIGATION

RULES OF THUMB

- DECREASES AS FREQUENCY INCREASES
- DECREASES AS WATER CONTENT INCREASES
- DECREASES AS CLAY CONTENT INCREASES
- DECREASES AS SCATTERING INCREASES
- INCREASES AS TRANSMITTER POWER AND RECEIVER SENSITIVITY INCREASE

GPR RECEIVED SIGNAL AND GRAPHIC PROFILE DISPLAY



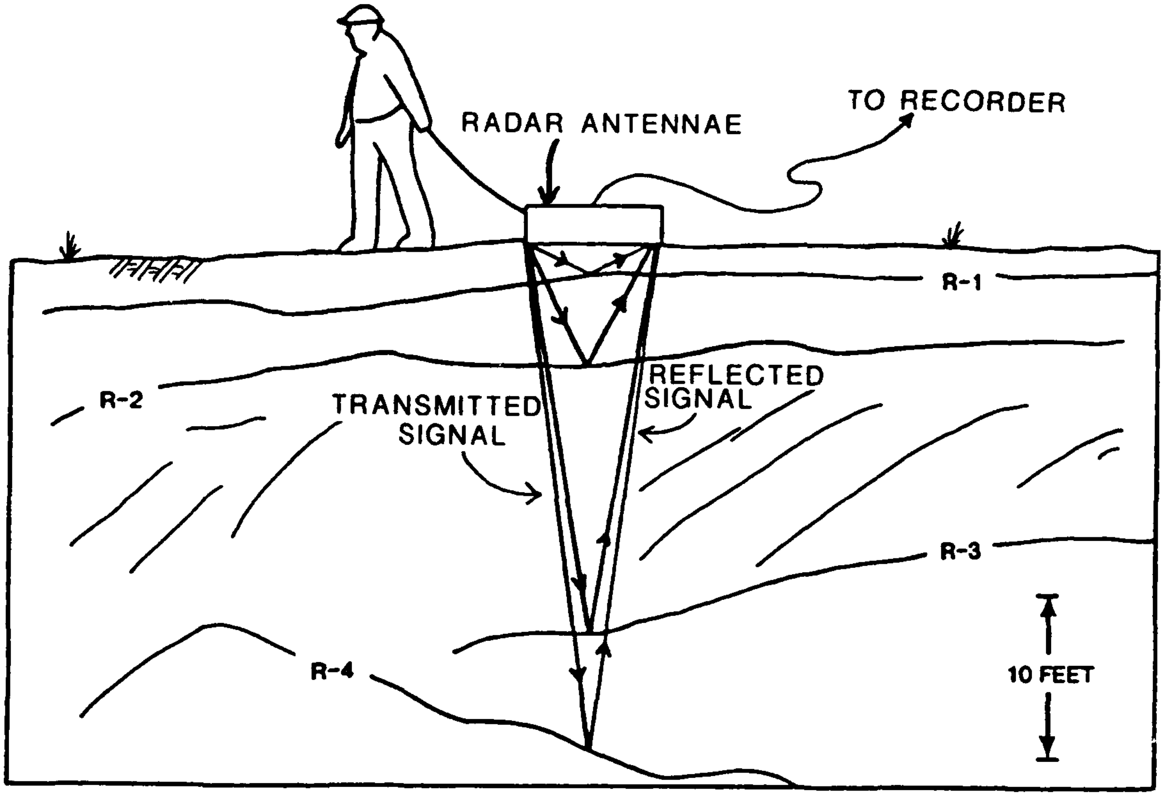
SKETCH OF TYPICAL
SINGLE WAVEFORM

GRAPHIC RECORDER REPRESENTATION OF
MULTIPLE WAVEFORMS ALONG A PROFILE

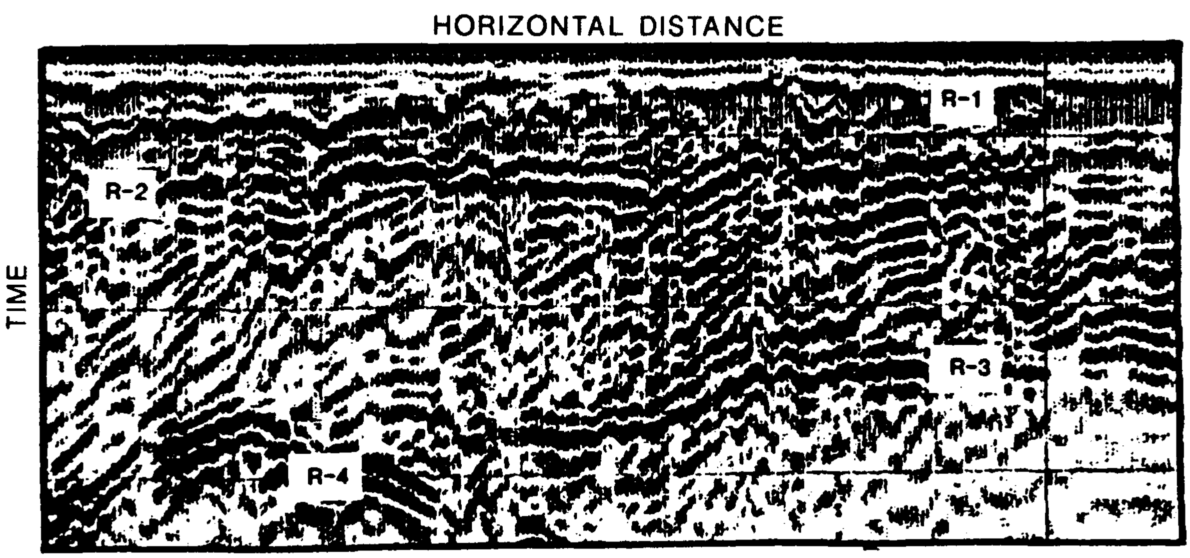
A Matter of Time

PROPAGATION MEDIUM	PROPAGATION SPEED, M/S		PROPAGATION TIME OVER 1 METER	
	Seismic Waves	EM Waves	Seismic Waves	EM Waves
Air (k = 1)	335	3×10^{8}	3 millisec	3.3 nanosec
Water (k = 81)	1500	3.3×10^{7}	0.7 ms	30 ns
Granite (Dry) (k = 5)	5000	1.3×10^{8}	0.2 ms	7.7 ns

NOTE: Wave Speeds in Air and Water Effectively Bracket EM Propagation Speeds in Geologic Materials.



GPR SURVEY OVER GEOLOGIC SECTION, REFLECTORS R-1 -- R-4



GRAPHIC RADAR RECORD FOR ABOVE SECTION

GROUND PENETRATING RADAR SURVEY CONCEPTS

Overview of Key Geologic Factors Effecting GPR Performance

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Performance of Ground Penetrating Radar (GPR) in various types of soils, rock, and site conditions can be predicted with reasonable certainty. It is possible to anticipate the GPR's depth of penetration and object resolution with a preliminary site investigation. Reasonably sufficient information to assess the applicability of GPR can be found from a combination of (1) Soil and rock descriptions from borings and cores, (2) Depth to the ground water table and water salinity, (3) The apparent resistivity of the materials with depth, (4) The measured or estimated materials permittivity or dielectric, and (5) Estimated depth, roughness and size of the reflector(s) of interest.

Penetration of GPR with a high resolution sounding capability of 10's of meters can be achieved when the material is dry sand, gravel or salt with low conductivity and low effective permittivity (dielectric constant). Adverse materials contain a high conductivity, a high permittivity and a high magnetic susceptibility. Materials such as brine saturated sands, fat clays or black sands (high magnetite or ilmenite content) do not easily pass the radar waves of interest. Penetration of GPR in such conditions may be less than a meter. Most realistic applications of interest fall somewhere between these two extremes and it is up to the knowledgeable investigator to assess the probability of success given data on the site conditions. Generally the material must have more than a few volumne percent magnetite to contain an adverse magnetic susceptibility for GPR. The DC conductivity of the material may be relatively easily measured or estimated from material properties. The effective permittivity (or dielectric) may be measured with a GPR unit in the field or more typically estimated from material type. With this information the attenuation of signal (hence depth of penetration) and object - boundary resolution can be judged.

TESTING FOR UNMARKED GRAVES

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There are many abandoned and neglected cemeteries in this country. At some of these, few or none of the graves may be marked. Ground-penetrating radar can sometimes aid in the location of individual unmarked graves; it may also help to delineate the boundaries of cemeteries, even if individual graves cannot be reliably detected.

The most reliable characteristic of a grave may be a distinct radar echo at a depth of a few feet. The echo arcs near the right hand side of Figure 1 are caused by three coffins.

There is an extreme range in the success of radar for locating unmarked graves. I have used radar at about two dozen sites where unmarked graves were possible. As an average, it appears that roughly a third of the graves could be identified on the radar profiles. Perhaps about a half of the echoes which were interpreted as being graves were not actually caused by graves. If fainter and less distinct echoes are interpreted as graves, both the rate of success and the rate of false alarms will increase.

Prehistoric or native American graves will generally be more difficult to locate than modern graves. This is because they can be simpler and shallower. At a shallow depth, stones and tree roots can cause so many echoes that graves cannot be isolated. Figure 2 illustrates a possible prehistoric burial. Illegal graves may be even more difficult to locate. There may be only one or a few and the area of search may be large.

Here is an example of the amount of time required for the search for individual graves in an area of 3.8 acres. The area was wooded, but cleared of brush. Parallel radar profiles were spaced by 5 ft. A total of 86 field hours was required for gridding the site and profiling a length of 6.3 line miles. In unwooded areas, one can survey about twice this rate. If careful location of graves is needed, profiles may need to be spaced by 2.5 ft and perpendicular lines may also be necessary.

If the survey of an entire site may require a few days of field work, you might consider a preliminary one-day test. If there are any marked graves, these can provide a good calibration. However, remember that the markers could be in the wrong place. Archaeologists will provide key advice and coordination for these radar surveys.

Additional examples of radar and EM detection of graves can be found in Bevan (1991). Magnetic (Brock and Schwartz 1991) and resistivity (Ellwood 1990) surveys can also aid in the location of graves.

References

Bevan, Bruce W., 1991, The search for graves: Geophysics, 56, 1310-1319.

Brock, James, and Steven J. Schwartz, 1991, A little slice of heaven: Investigations at Rincon Cemetery, Prado Basin, California: Historical Archaeology, 25, 78-90.

Ellwood, B. B., 1990, Electrical resistivity surveys in two historical cemeteries in northeast Texas: A method for delineating unidentified burial shafts: Historical Archaeology, 24, 91-98.

Notes on the figures

Figure 1: This site is at St. Mary's City, Maryland. The radar profile crosses the foundations of the Great Brick Chapel. The largest lead coffin may contain the body of Philip Calvert, a 17th century governor of Maryland. This survey was done for Henry M. Miller, the director of research for Historic St. Mary's City; it was sponsored by the St. Mary's City Foundation. The radar survey was done on March 20, 1989, and the profile was made with a model 3102 (180 Mhz) radar antenna with a SIR System-7 radar. The depth scale assumes a pulse velocity of 0.27 ft/ns and the soil is sandy.

Figure 2: This is the Little Bear mound at Effigy Mounds National Monument, north of Marquette, Iowa. While mounds were sometimes used for human burials, it is not known if this feature is a burial. The survey was done on November 12-13, 1981, and coordinated by Robert Nickel; the project was sponsored by the National Park Service. A model 3102 antenna generated this profile and the depth scale assumes a pulse velocity of 8.5 cm/ns. The soil resistivity drops from 360 ohm-m to 35 ohm-m at a depth of about 45 cm.

Figure Captions

Figure 1: Excavation of the area on the right side of this radar profile revealed three lead coffins. The underground brick foundations cause reverberating echoes. Tic marks at the top of the profile indicate 5 ft intervals.

Figure 2a: The outline of a prehistoric effigy mound is shown here; the feature mapped within it was located by the radar.

Figure 2b: A cross-section of the span A-B as a radar profile; this echo may be caused by a grave.

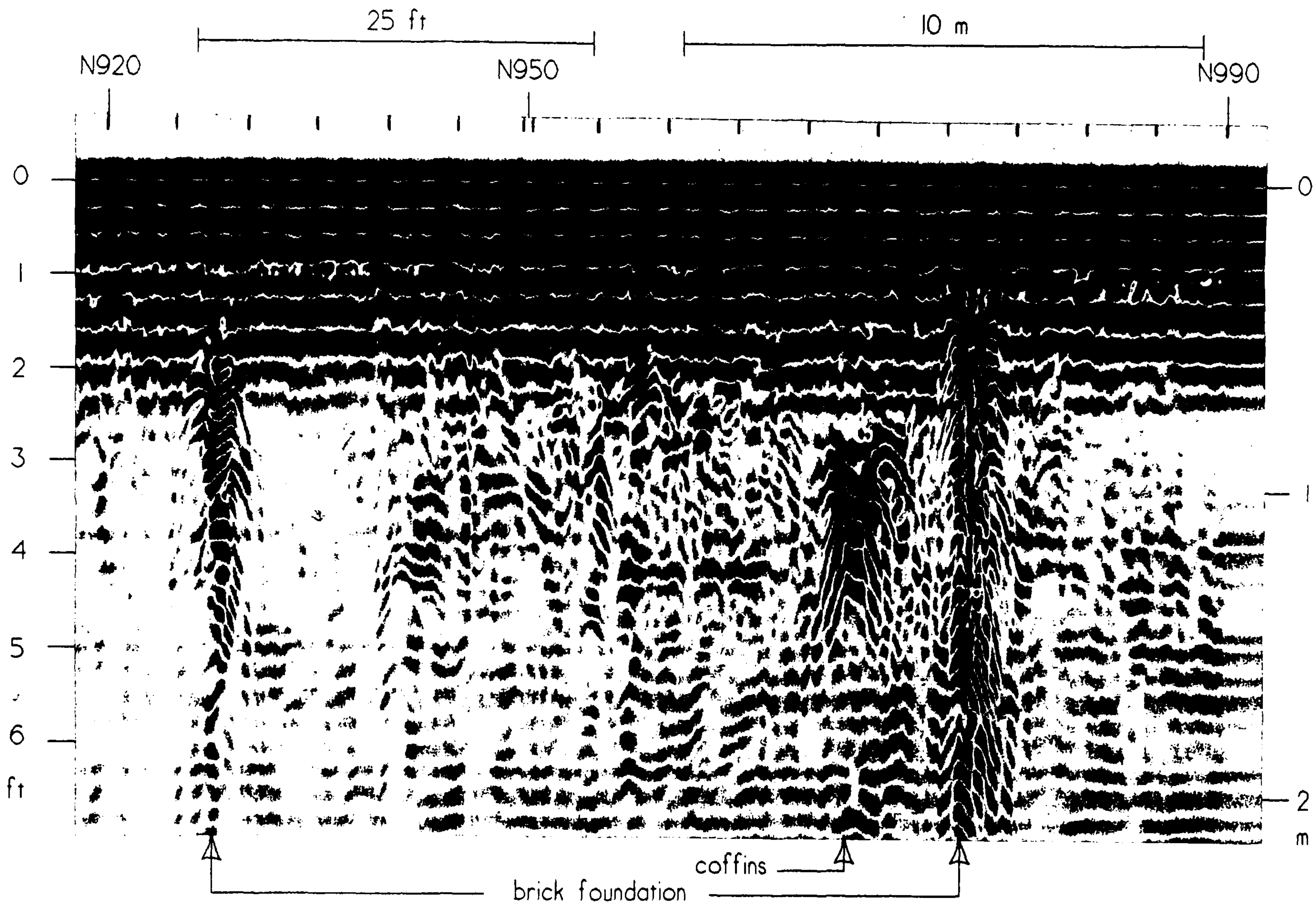
25 ft
10 m
N920
N950
N990
0
1
2
3
4
5
6
ft
0
1
2
m
coffins
brick foundation

Figure 1.

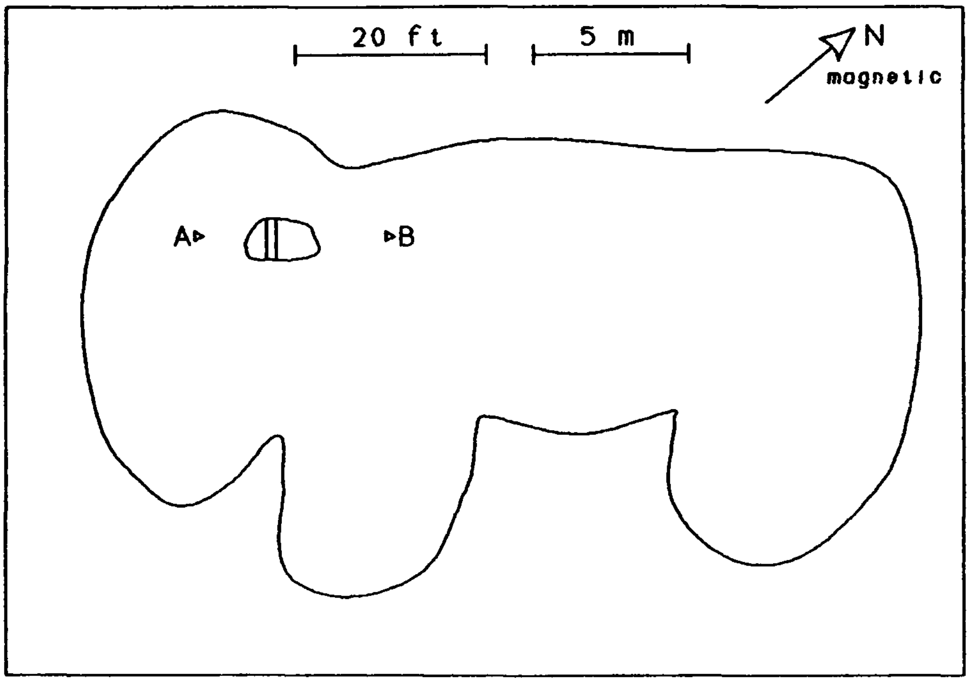

Figure 2a.

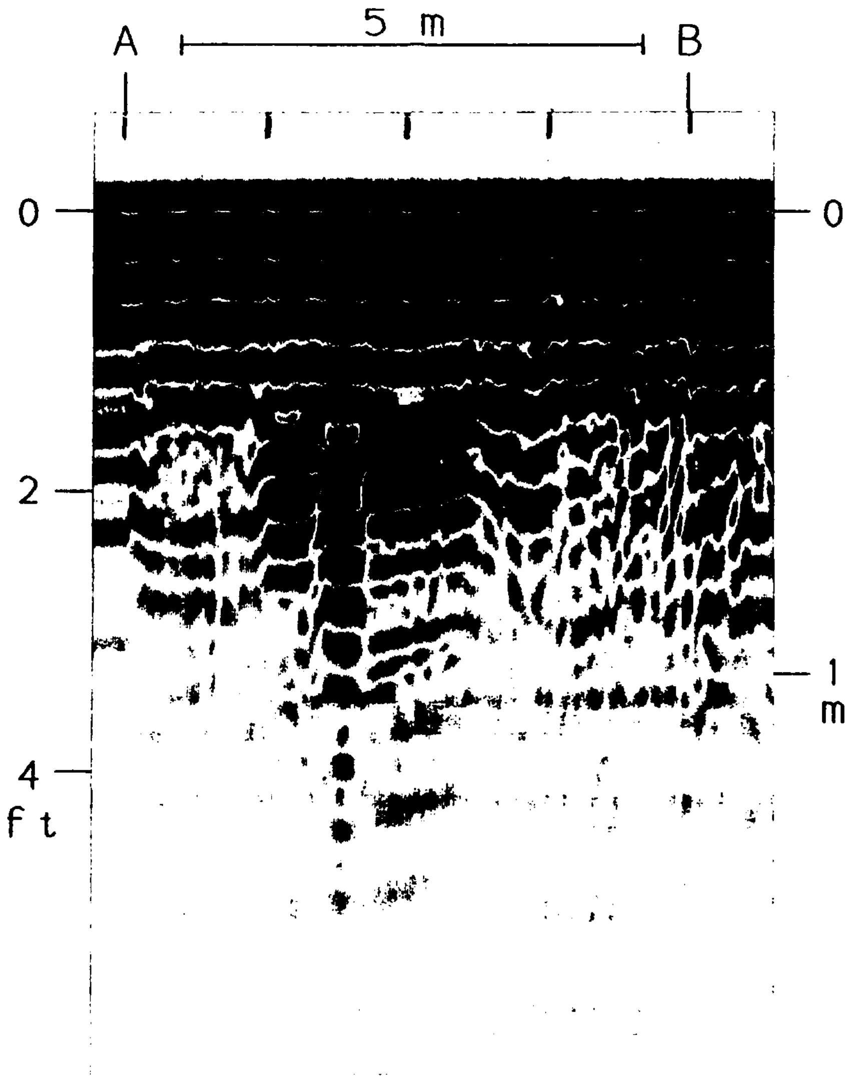

Figure 2b.

FRACTURE AND CAVITY DETECTION AND MAPPING WITH GROUND PENETRATING RADAR - AN OVERVIEW WITH EXAMPLES

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ABSTRACT

There is a wide range of geophysical and non-geophysical methods that can be used to locate and map fractures and cavities. Ground Penetrating Radar is one of the surface geophysical methods that has been successfully applied to a wide variety of projects. Ground Penetrating Radar has the highest resolution of any surface geophysical method, it provides a continuous profile data along the survey line and by running a number parallel survey lines one can approach 100% site coverage. In addition, the accuracy and precision of the method are extremely high. These features allow radar to be extremely effective for detection, mapping and monitoring of fractures and cavities. The primary limitations of radar include it s site-specific performance and depth limitation. Depth limitations can often be overcome by using near surface indicators of deeper geologic conditions. In many cases, the use of near surface indicators has allowed radar to succeed in areas where radar performance is poor such as in silty and clayey soils. Examples from a wide range of fracture and cavity assessments are included to illustrate successful applications of radar to these problems.

APPLICATION OF GPR FOR LOCATION OF OLD MINE WORKINGS

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A very common geotechnical problem is the detection of abandoned underground workings. In Canada most of the underground workings which require detection are old mine workings underneath urban areas. The detection, delineation and remediation of these areas are costly time consuming exercises. Over the past 5 years a number of sites have been investigated using GPR and this case history will provide a couple of examples of work carried out in this area.

In most instances, ground penetrating radar response over old mine workings does not have the *distinctive* behavior one would anticipate. In ideal situations, a cavity or opening in rock when detected with GPR will give rise to a localized response which is hyperbolic in shape. In practice however, it is found that there is seldom such a simple response. In many of the application areas where we have used radar, we find that there is a whole host of responses and increase in volume scattering but not the classic anticipated hyperbolic response. The explanation for this is attributed to the fact that many of the workings are the product of drill and blast mining or that the rock over the openings is in poor condition and is highly fractured and unstable. In both cases, the broken and damaged nature of the rock gives rise to a multiplicity of responses which masks the simpler large cavity beneath.

In some areas strong responses have been observed in the overburden above areas where mining has been carried out. In these instances, it is believed that the mine workings have damaged the rock above the working and also changed the consolidation and water drainage in the overlying soils. As a result, strong distinctive responses have been seen in the overburden but the actual mine workings have not been detected.

Case histories from several locations will be used to illustrate these points. In general all of the radar survey work has been carried out in conjunction with drilling programs and geotechnical remediation work. As a result, good control on the nature of the ground conditions is available.

The Detection and Location of Abandoned Gas Wells in Coal Seams by Ground Probing Radar (GPR)

by

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Summary:

Numerous gas wells were drilled in the Appalachian area some one hundred years ago. These wells were subsequently abandoned, and in may cases, when possible, the telescoped steel pipe was reclaimed. Thus, the current situation exists where evidence exists on the surface, or on old maps, of the existence of these old wells. They probably intersect the coal seam to be mined and, thus, present a safety hazard to the miners.

The two conditions associated with these wells are: 1) the drift of the well is unknown, and 2) the portion of the well through the coal seam may be lined with steel pipe and most probably is filled with debris and dirt.

The current acceptable, costly procedure is to redrill these old wells, insert a small steelpipe (i.e. 4" diameter) beyond the coal seam, and then force concrete down the pipe until it comes to surface outside the pipe. The mining equipment can then safely mine through this well.

If the well can be accurately located from a face in the coal seam, then the mining equipment could potentially mine much closer than is currently allowed. More importantly, new technology is emerging which may make it possible and acceptable for plugging the well from these shorter distances.

We have employed a short pulse GPR on several of these old wells (cased and uncased) with very good results out to distances beyond 50 feet. We have collected and analyzed data from 3 newly drilled test wells for distances ranging from 15 to 50 feet. Several radar collections were made where these wells had no pipe in them, steel pipe in them, and drillers mud in them. We obtained good detection and location signatures for most of these cases, Many surveys were accomplished primarily using different antenna frequencies and monostotic and bistatic methods of data collection.

In conclusion, we have demonstrated that the GPR is an excellent system for detecting and locating these old gas wells for distances in excess of 50 feet. In order to determine the maximum possible distance will require more tests with wells out to distances between 50 and 200 feet.

APPLICATIONS OF GROUND PENETRATING RADAR IN THE GEORGIA COASTAL PLAINS

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Expanded Abstract

Soils developing in the coastal plains region of Georgia vary in depth, texture, depth to water table, and various other chemical, physical, and morphological properties. Researchers at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Southeast Watershed Research Laboratory (SEWRL) in Tifton, Georgia, need improved and cost-efficient ways to determine lateral extent and depth of diagnostic features found in these soils and how depths vary with horizontal distance. They have used ground penetrating radar (GPR) to investigate soil properties (and their spatial variability) and geologic materials in this region. The GPR unit used by researchers at SEWRL is a Geophysical Survey Systems, Inc. Subsurface Interface Radar (SIR) System-8 impulse radar. This GPR unit is a broadband, video-pulse radar that provides a non-destructive, continuous image of subsurface interfaces. The time-scaled radar system measures the time a shortwave electromagnetic pulse takes to travel from an antenna to a detectable subsurface interface (with contrasting dielectrics) and be reflected back to the antenna. Three antennas with frequencies of 80, 120, and 500 MHz have been used. However, most studies conducted at SEWRL, and discussed here were done with the 120 MHz antenna. GPR has been used by researchers at SEWRL to map soils and do non-destructive site investigations, detect and determine spatial variability of argillic horizons, determine depth and spatial variability

of water tables in coarse-textured soils, determine depth and lateral extent of geologic materials, locate and determine depth of hard pans, and map lake bottoms and define lake storage conditions.

Researchers at SEWRL are identifying and describing mechanisms and processes controlling water and agrichemical (nutrients and pesticides) movement in coastal plain soils. Quality of shallow/perched and deep groundwaters is a major concern at SEWRL, and loss of agrichemicals from root and vadose zones is potentially greatest from soils of this region. GPR is a valuable research tool because it provides a continuous, non-destructive profile of many subsurface features found in these soils in a relatively short period of time, and researchers can use GPR to relate soil features between specific sites where data has been collected. GPR has many applications in various studies being conducted at SEWRL. This paper will present past and current applications of GPR at SEWRL, problem areas/limitations of GPR in our research, and future research opportunities and needed development for GPR.

ROLE OF GPR IN INTEGRATED GEOPHYSICS ASSESSMENTS

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ABSTRACT

Ground penetrating radar (GPR) is almost never used as a stand-alone method in engineering, geotechnical, and environmental applications. Three brief case histories are presented which illustrate the role of GPR in an integrated geophysics program: Beaver Dam, Arkansas; Mill Creek Dam, Walla Walla, Washington; Defense Depot Ogden, Utah.

The geotechnical objectives at Beaver Dam were the detection and mapping of anomalous seepage paths through and under a large dike, mapping the bounding fault zones of a graben underlying the dike, and mapping of solution features, including a highly irregular top of rock, in the limestone and dolomite foundation of the dike. GPR was used in conjunction with seismic refraction, seismic reflection, electrical resistivity sounding and profiling, electromagnetic profiling, and self potential surveys. GPR was successful in mapping the width of the bounding fault zones, detecting solution features and fractures in the limestone and dolomite, mapping the irregular top of rock, and contributing to the overall anomalous seepage assessment.

Mill Creek Dam has experienced anomalous seepage, including piping of silt foundation materials, through the dam foundation since its first test filling in the 1940's. GPR was used in conjunction with microgravimetry, seismic reflection, electrical resistivity, electromagnetic methods, and self potential surveys to map anomalous areas in the right abutment area of the dam. GPR was able to achieve only approximately 5 m depth of investigation in the silt materials. GPR succeeded in verifying uniformity of conditions laterally to a depth of 5 m along the upstream toe of the dam in the right abutment area. Also, in the floor of the reservoir (dry), GPR was utilized to produce a high resolution mapping of a filled sinkhole; the GPR records also suggested vertical pipe features below the sinkhole, suggesting migration pathways for water and silt.

An approximately one acre site was investigated at Defense Depot Ogden to locate buried hazardous materials. The interior portion of the site was surrounded by an 8-ft high chain link fence. GPR, magnetic, and electromagnetic surveys were conducted at the site. All three types of surveys were affected to some extent by the chain link fence. GPR was successful in locating buried metallic objects and mapping a burial trench. The GPR signature of the fence could be recognized as a prominent dipping feature as the fence was approached during a GPR survey line. An integrated methods anomaly map was prepared for the site.

APPLICATIOM OF GPR TO CONTAMINATED GROUND WATER MAPPING

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Ground penetrating radar systems provide a very sensitive method for detecting changes in electrical properties in the subsurface. As a result, GPR offers considerable potential for mapping the presence of contaminants in the subsurface. The key to effective use of GPR requires the presence of a contaminant which has impact on the electrical properties. For example, leachate contaminants from a landfill site increase the chloride content of the water which boosts its conductivity and hence makes it opaque to radar signals. The presence of a DNAPL which is a low dielectric constant immiscible liquid which displaces water from the pore space results in a drop in dielectric constant in water saturated materials and is hence detectable by GPR.

In the present case history, we will provide an overview of surveys carried out as well as example data from sites such as this. The first example demonstrates data from a known landfill site. The second one is from a controlled spill experiment conducted by The University of Waterloo. While these data are from very simple geological settings, they do demonstrate that radar can be effectively employed for this application provided that the geological setting is not too complicated. In many real spill areas the interpretation is much more complicated and requires considerable control from other investigations, i.e., borehole and geophysical methods.

Use of Ground-Penetrating Radar within the USDA-Soil Conservation Service

James Doolittle*

Since 1981, the Soil Conservation Service (SCS) has evaluated the performance of ground-penetrating radar (GPR) on a wide variety of soils and geologic materials in diverse geographic locations. Depth of interest is commonly 0.5 to 2.0 m, but ranges from 0 to 15 m.

Ground-penetrating radar has been used primarily to assess properties of soils that affect their use, management, and classification. GPR techniques have been used to chart the lateral extent and depth to soil horizons; map soils; delineate water table and bedrock surfaces; assess soil compaction and hard pan development; and infer changes in soil texture, organic matter content, humification, and cementation.

Though used principally to support soil survey operations over broad areas, GPR has been increasingly applied to archaeological, engineering, and geologic site assessments. This technique has improved the understanding of spatial variability of soil and geologic materials, increased the depth and area of observations, facilitated site planning and excavation strategies; and, as precursors to site selection, reduced unnecessary or unproductive expenditures of resources.

Studies have shown that the GPR can provide accurate and graphic information, greater depth and areal coverage per unit sampled, and higher levels of confidence in site assessments. In some soils, ground-penetrating radar has proven to be a rapid, cost-effective, and nondestructive method for soil investigations and site assessments. However, with the exception of Florida and Massachusetts, GPR has not been integrated into routine field investigations and sampling activities conducted by staff specialists. The use of GPR within SCS remains confined because of the equipments relatively high costs, limited success in high-loss mediums, site-specific nature, and interpreter dependency.

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A FM-CW RADAR USED FOR PROBING OF BRICK STRUCTURES

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PRELIMINARY ABSTRACT

A special purpose FM-CW radar system was developed at Southwest Research Institute (SwRI) and has been used for several applications. The system uses a YIG-tuned oscillator sweeping over a range of 2-6 GHz. The output of the oscillator is time gated (RF switch) over a programmable sweep range. Output frequencies are mixed and translated to the VHF/UHF range. Thus, by adjusting the sweep frequency range (digitally), the system performance can be optimized from 30 MHz to 1 GHz to provide the best penetration and target resolution for the media being probed.

The first application of the system was in the inspection of subway tunnel walls. These measurements were conducted using TEM dielectrically-loaded horn antennas which were developed originally for an pulse ground penetrating radar (GPR) designed for the U.S. Army.

Major subway tunnels built in the late 1800s in New York are still being heavily used today for public transportation in rail systems operated by the Port Authority Trans-Hudson Corporation (PATH) and the New York City Transit Authority. Because several of these subway tunnels are strategically located and are now sagging, it has bee necessary to assess the structural integrity of the brick walls using nondestructive techniques to identify any potential safety hazards that might exist or develop with continued use. The specific task for PATH was to study brick-lined tunnels under the Hudson River that have water-saturated walls with a thickness of six to eight courses. The tunnels were constructed with an exterior steel liner bolted together at flanged joints. Before the project, there was a question about whether the steel liner was still intact.

Tests were conducted in two brick-lined tunnels. The first tunnel was an unused drift tunnel in which long uninterrupted work periods could be spent obtaining representative scans. The second tunnel is in use by west-bound trains from Manhattan to New Jersey. The two tunnels run parallel within a few feet of each other and were similar in electrical characteristics.

In general, the FM-CW radar signals were able to penetrate the brick-lined tunnel walls. Analysis of the reflected signals showed that the steel liner is apparently intact. After the field tests were completed, the steel liner was physically verified in the drift tunnel by taking core samples from the walls.The radar responses of the walls in the active tunnel were similar to the responses obtained in the drift tunnel.

APPLICATION OF MAXIMUM ENTROPY TO GPR (THE PHASE METHOD OF ECHO IDENTIFICATION)

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Abstract:

Ground Penetrating Radar [GPR] can fill a great need, but it is faced with problems such as echoes which are closely spaced to the transmitting signal, overlapped echoes, and a bandwidth which is limited by the ability to generate signals and the high losses incurred by the passage through the ground and its interface. A signal analysis method which shows potential for mitigating some of these problems is presented. Information in the radar signal's phase can be readily extracted, allowing separation and identification of overlapping echoes. The ability to generate arbitrary signal waveforms is limited by the transducer structure. However, the ability to process the signal has been demonstrated in our earlier work, in which clear resolution of closely spaced echoes is achieved. The technique takes advantage of the broad bandwidth available in the echo modulated signal. By using phase recovery methods, based on noise reduction methods which are well established in the entropic signal processing community, significant improvement can be achieved. We have demonstrated that this is achievable in a one dimensional series of tests. An analysis of this method is presented.

The Use of Phase in Echo Identification

The problem of echo identification can be shown for the example of a cosine wave,

$$s(t) = \cos(\omega t)$$

When an echo occurs, of fractional amplitude a_o, at time t_d, then the combined signal is

$$x(t) = s(t) + a_o\, s(t - t_d) = \cos(\omega t) + a_o\, cos(\omega(t - t_d))$$

If we express the sum of two sinusoids as a single sinusoid, we have

$$x(t) = \sqrt{1 + a_o^2 + 2a_o \cos \omega t_d}\, \cos(\omega t - \theta)$$

The phase term, however is

$$\theta = Arctan(\frac{a_o \sin \omega t_d}{1 + a_o \cos \omega t_d})$$

For small reflection coefficients, a_o, the denominator of the last term is approximately unity, and the value of the Arctan of an argument and the value of its argument are approximately equal, thus,

$$\theta \approx a_o \sin \omega t_d$$

The method also allows superposition and identification of multiple echoes. If there were two echoes, then amplitudes of echo might be a_o and a_1. The sum of two sinusoids is similarly

$$x(t) = \cos(\omega t) + a_o \cos(\omega(t - t_{do})) + a_1 \cos(\omega(t - t_{d1}))$$

If we concentrate on the phase, we have

$$\theta = Arctan[\frac{a_o \sin \omega t_{do} + a_1 \sin \omega t_{d1}}{1 + a_o \cos \omega t_{do} + a_1 \cos \omega t_{d1}}]$$

Again, small reflection coefficients allow approximating the denominator by unity. Small angles yield the numerator as a sum of the individual phase shift terms, preserving linearity. This asssures superpositon in the phase term.

Digital Sequences to Extract Phase Information

The radar signal's time sequence, x(n), which is x(0), ..., x(M), can be written as an even and an odd part. The even part is e(0) ... e(M), where

$e(n) = (x(n) + x(M-n))/2$

and an odd part, o(1) ... o(M),

$o(n) = (x(n) - x(M-n))/2.$

Each sequence, e(n) and o(n) will have M + 1 terms.

We note that the Fourier transform of an even function is pure real, while the Fourier transform of an odd function is pure imaginary. The power spectrum, then will be made up of these two orthogonal components, as

$$S_{xx}(\omega) = S_{ee}(\omega) + S_{oo}(\omega)$$

Of course, even and odd are referred to the origin, so we have a referenced displacement of our origin by N_S samples, to the center data point. Of course, the results of our analysis will also be displaced by N_S samples. We can define the phase, using the orthogonal components of the Fourier transform, E(ω) and O(ω). Then

$$\theta(\omega) = Arctan[\frac{O(\omega)}{E(\omega)}]$$

At this point, it is useful to use the trigonometric identity

$$\cos[2\theta] = \cos^2\theta - \sin^2\theta$$

where

$$\cos\theta = \frac{E(\omega)}{\sqrt{E^2(\omega) + O^2(\omega)}}$$

$$\sin\theta = \frac{O(\omega)}{\sqrt{E^2(\omega) + O^2(\omega)}}$$

and using the trigonometric identity for cos(2θ)

Also, writing the $\cos^2$ and $\sin^2$ over a common denominator, we have

$$\cos 2\theta = \frac{|E(\omega)|^2 - |O(\omega)|^2}{|E(\omega)|^2 + |O(\omega)|^2}$$

$$\cos 2\theta = \frac{S_{ee} - S_{oo}}{S_{ee} + S_{oo}}$$

If we use the maximum entropy method to evaluate the spectral components, we will have spectral estimates which do not suffer from the spectral leakage associated with the Fast Fourier Transform. Additionally, we note, the maximum entropy filters are minimum phase, and this last relation converges for all values of ω.

The time of delay, t_{d_single}, can be found from

$$\cos 2\theta(\omega) = \cos[2\omega t_{d\_single}]$$

The 2 in the left hand side comes from the trigonometry identity, the 2 in the right hand side comes from the round trip distance. (The reason that a_0 does not show up explicitly is that it is contained in both the even and odd sequences and their transforms.)

All the sequences were computed using N_s, the center of symmetry. However, t_d is the round trip delay (twice t_{d_single}), whether you talk about referenced to N_s (i.e., delay with respect to N_s, using N_s as reference) or with respect to leading edge (i.e., delay of echo with respect to leading edge, with original signal referenced to leading edge). Of course, since leading edge can only be original signal, this is the more logical place to use (rather than reset both original wave and delay to mid point)!

Maximum entropy, then, provides a convenient signal processing method for overlapped echoes. An example is shown in the next section, for a sonic signal. Its echo pattern lies mainly within the time of the sending signal, yet echo identification is quite good.

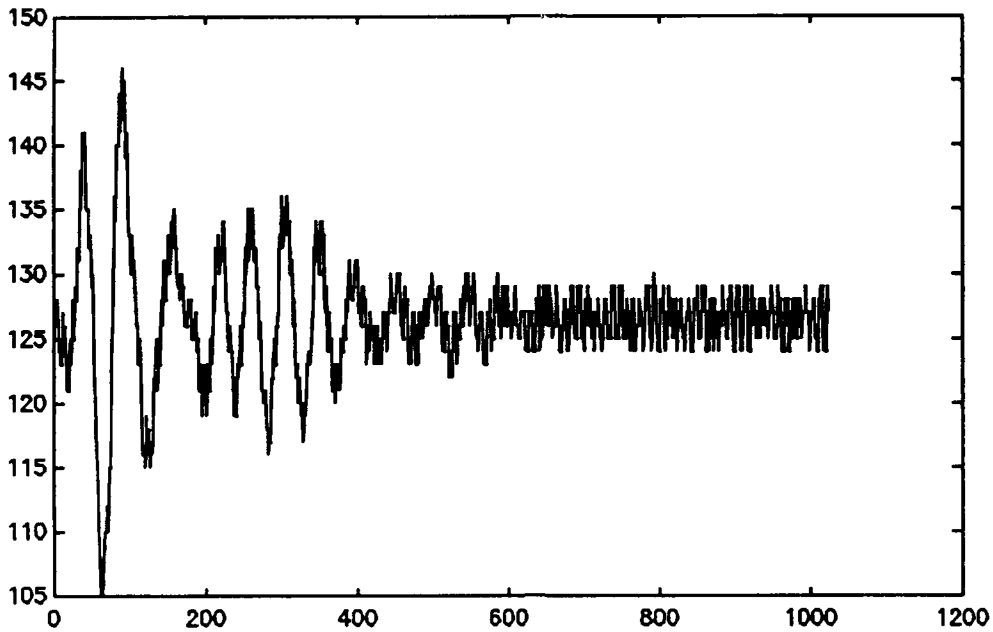
The similarity of the signal waveform which Dr. David Cowling presented to the example here is our basis for trying this technique in the GPR problem.

Method

The method of processing requires one to process the signal to extract an estimate of the phase of the signal. This estimate is made using the Maximum Entropy Method [MEM], which makes optimum use of the available data, without assumptions about non–available data. This is in contrast to the Fast Fourier Transform [FFT] and use of the Wiener Kintchine theorem, where assumptions are made about non–available data. In the case of the FFT, the assumption of periodic intervals is made; in the second case, assumptions of padding the data with zeros are made.

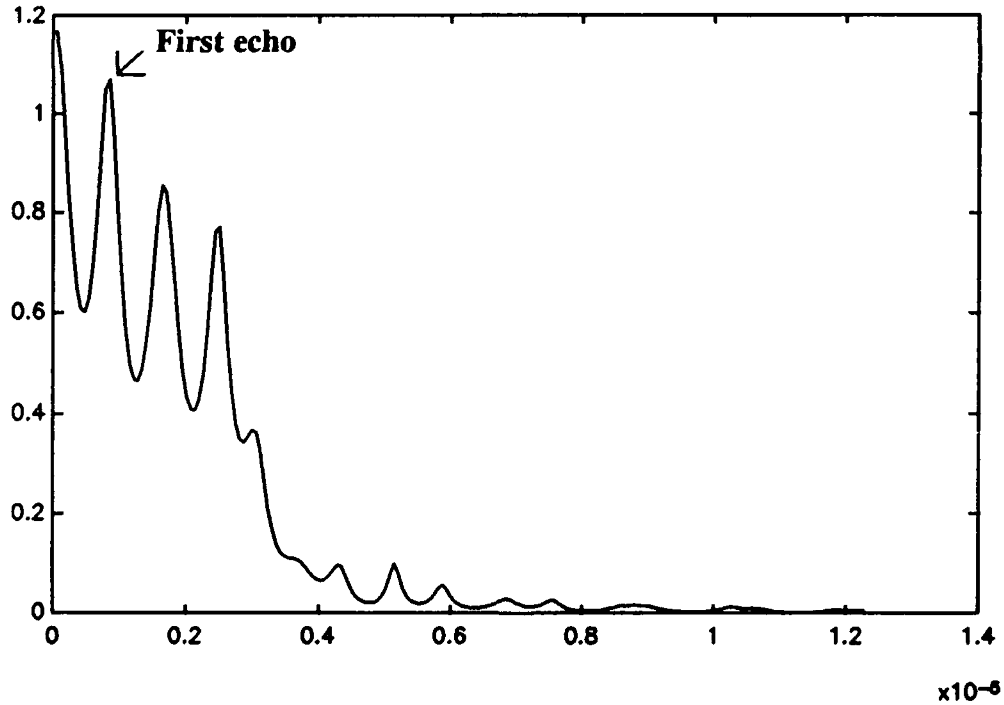
The method which we wish to use allows separating overlapping echoes without resorting to assumptions of the impulse response of the system. Trying to invert an assumed transfer function generally results in ill–conditioned problem. In utilizing the MEM, we obtain a robust technique for phase estimation.

That this method works extremely well (providing a level of echo identification not currently available by other methods) might be seen from the graphs of the original signal and the restored signal for echo identification, shown below. We have successfully demonstrated this method in two dimensions, though the reduction to a suitable three dimensional display is being prepared at this time.



Time domain signal (scaled voltage) versus data sample point.

Each data point above represents approximately 10 ns.



Reflected amplitude (relative amplitude) versus time (s).

The first echo appears at 1 μs, as expected for this test. Multiple echoes (higher order) can be seen. The original signal, a damped sinusoid, overlaps the echo, which makes the unprocessed signal useless for indentifying closely spaced objects. The processed signal, in contrast, clearly identifies the echoes. This method is sufficiently unique to be recognized by a patent to one of the authors (Roemer) .

THE USE OF GPR IN TRENCHLESS EXCAVATION

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ABSTRACT

An overview of applications of GPR for use in the area of trenchless technology are investigated. This general overview is to be followed by the application of doppler techniques to trenchless technology. The results of laboratory measurements of these techniques for application to active systems employed at the cutting head are discussed.

INTRODUCTION

Trenchless excavation is the laying of small or large paths, holes or conduits under the surface of the ground without disturbing the surface. Applications include the jacking of a simple water pipe under a roadway or even a driveway to the installation of very large conduits under major water ways. In all cases one of the problems which the contractor faces in the trenchless excavation is the location of the path and of the head during the boring or jacking process. As might be suspected the path of a jacked pipe and more surprisingly the path of a seemingly rigid 60" diameter casing will not be straight line. There are all sorts of reasons for this action ranging from the *nonuniformity of the medium through the operations* are being carried out to the the boring heads predetermined preference for a certain cutting direction. These trenchless systems many times employ internal methods for guidance. The problem which appears is if you know where the system is supposed to be, you must know where it is now in order to guide it to the location which you wish. For a lot of crossings the location isn't all that important. If you miss your mark on the other side of a 150 foot bore by 2 feet this doesn't cause a problem. However, increasingly this does become important. If you are laying a sewer or drainage line then absolute adherence to a specified grade is absolutely required. If you are tunnelling between manholes, then you must hit the target manhole. In built up areas you often have other services near by and these must be missed. If they are struck, then service down time and associated financial burdens are placed upon the contractor.

Not surprisingly there are a large number of systems available for locating the path of a trenchless excavation. However what is surprising is that the accuracy, the range, or the applicability of these systems may be short of the requirements of the project. Trenchless instrumentation for tracking the location of the bore falls into two general categories. The first is that of survey. These systems require the shutting down of the operation and then a survey to find what has happened. The second general classification is known as steering tools. These also fall into two separate subcategories. Those that are wire connected (called steering tools) and those which are connected via EM, acoustic or pulsed mud means (called MWD, Measure While Drilling). The instrumentation technologies employ sensing means which range from walk over using EM, magnetic induction, or acoustic means to MWD using lasers and targets, homing on EM field, or gyroscopes and accelerometers.

Large diameter boring systems, Examples are tunnels or very large casings will make use of laser technology and EM homing systems. A Tokyo construction company has developed a radar device which looks through a window in the bore cutter to give immediate soil conditions ahead and to each side of the bore and at the same time will also give warnings of obstructions in the bore path. The look ahead distance for this device is 7 to 10 feet ahead of the cutter. In general for large diameter boring systems, instrumentation is available to allow both grade and horizontal path be maintained in a manner which would meet specifications for these type of excavations.

The technology is such that, for very small diameter rod pushers and piercing tool, that short range homing beams using either magnetic induction or EM waves have proven to be quite successful. The range of the EM homing beacons used is near 150 feet. The arena where there doesn't seem to be good solutions is that of medium size pipe and casing having diameters of 20 to 60 inches. If the area has surface access and provided the depth is within reason, then surface walkover with a sonde in the casing will yield position or the casing may be tagged with a low frequency signal and located with a pickup loop sensing the magnetic portion of the near field. For a number of conditions surrounding a project, these methods may be unsatisfactory. For these cases accelerometers and or gyroscopes may be used in an integrating, dead reckoning system. Tests of some of these systems have not shown the accuracy which may be desired.

DOPPLER APPLIED TO GPR

One possible solution to the tracking problem in medium sized trenchless excavation may be that of using methods of radio direction finding on head of the bore. In this proposed solution a transmitting radio collar would be attached to the outside of the boring head and would be arranged to either transmit a continuous radio signal, or to transmit a radio signal on command. Near the exit of the bore one or more arrays of receiving antenna would be set up. The antennas would be sampled in a rotating pattern. This sampling will give rise to a doppler shifted signal which may be detected by an FM receiver. The phase of the received doppler signal is compared to the phase of the signal used to switch the antennas in the receiving array. This phase comparison yields a linear function which is proportional to the bearing of the radio source (in this case the radio collar) relative to the receiving array.
In order to demonstrate how this might work, a simple, two element Adcock array is proposed. This is illustrated in Figure 1.

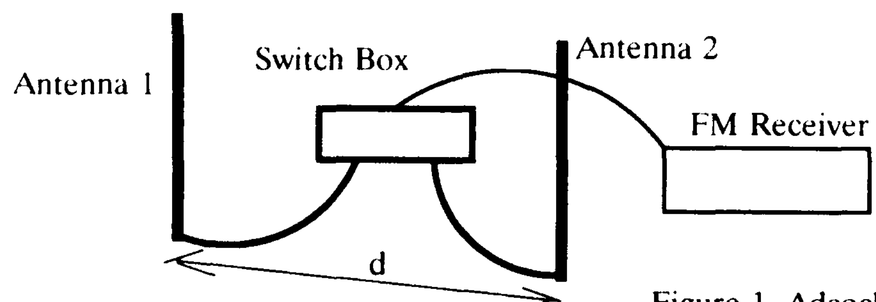

Figure 1. Adcock array set up for Doppler reception

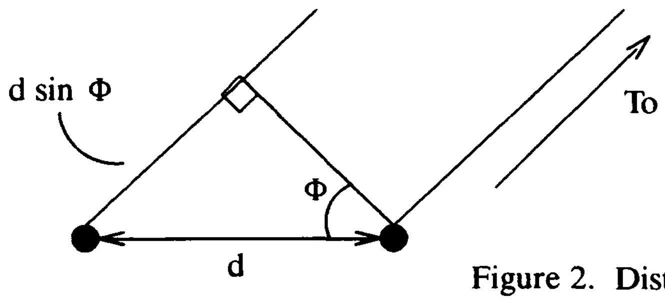

Figure 2. Distance between wavefronts

The distance between antennas measured perpendicular to an incoming wave front is given as d sin Φ. This distance may be turned into a phase angle in radians by dividing by the wavelength, λ, of the transmitted radio signal. Each antenna is sampled (in the switching box) at a rate of ω_m. This sampled wave form is then trunked to the FM receiver. This FM receiver sees a frequency modulated wave due to the sampling of the following form:

$$V_{FM}(t) \;=\; A\cos\{\,\omega_c t + k\,\text{rect}(\omega_m t)\,\} \qquad (1)$$

Where k is given as {d sin Φ}/λ. The first major Fourier component of this square wave function, k rect(ω_mt), has the value of (k / π). Only the first Fourier component is carried forward as the receiver bandpass filter will reduce higher components to second order quantities which do not need to be considered. Under this set of circumstances the frequency modulated signal which the receiver detects has the form:

$$V_{FM}(t) \;=\; A\cos\{\omega_c t + (k/\pi)\sin\omega_m t\} \qquad (2)$$

The instantaneous value of phase of this frequency modulated signal is:

$$\Theta_{inst}(t) \;=\; \{\omega_c t + (k/\pi)\sin\omega_m t\} \qquad (3)$$

The instantaneous value of the frequency of this wave is found by taking the first derivative:

$$\omega_{inst} \;=\; d(\Theta_{inst})/dt \;=\; \omega_c + (k/\pi)\omega_m\cos\omega_m t \qquad (4)$$

The term, ω_c, represents a DC term and this will not be passed on by the FM detector in the receiver. The output of the FM detector then will be:

$$V_{det} \;=\; (k/\pi)\omega_m\cos\omega_m t + \Psi_{noise}(t) \qquad (5)$$

This wave form is a sinusoid whose frequency is ω_m and whose amplitude is proportional the the value of k. For a two antenna system such as the one analyzed above the antenna system is turned until the value k disappears. This occurs when the value of Φ moves to 0 degrees. When this happens the antenna array is broadside to the incoming radio wave from the transmit antenna. The accuracy of such an arrangement is controlled only by the amount of noise, Ψ_{noise} present at the detector of the receiver. Since you are using FM modulation techniques the noise performance should be much better than the corresponding AM techniques. Laboratory measurements have shown this noise performance to be good enough in an inexpensive communications recei.er to allow angular determination to less than a degree of azimuth.

The system which has been just described has been called a Double Duckie in a large amount of hobby and amateur radio literature. If the two antenna elements are replaced with a series of 4 or 8 or a larger number, the antenna takes the form of a Wullenweber array. This array is switched, one antenna element at a time, as was the Adcock array. This switching occurs in a continuous fashion around the circle of antenna elements. The result of this switching is to cause a sampling of the wave front as it passes across the center of the array. This sampled wave front is contained in the frequency (phase) modulated portion of the signal which the receiver detects. The wave which emerges from the FM detector has the following form:

$$V_{det}(t) = K\omega_m \cos(\omega_m t + \Phi + \alpha) + \Psi_{noise}(t) \qquad (6)$$

Here (90 degrees - Φ) is the bearing from the array center to the radio source. The antenna scanning source, whose frequency is, ω_m, is also available and its phase is compared to the phase of this signal. The results of a linear phase detector applied to the two signals yields only the value of (90 - Φ), or the bearing to the radio source from the center of the antenna array. Figure 3 is a top view of such an array.

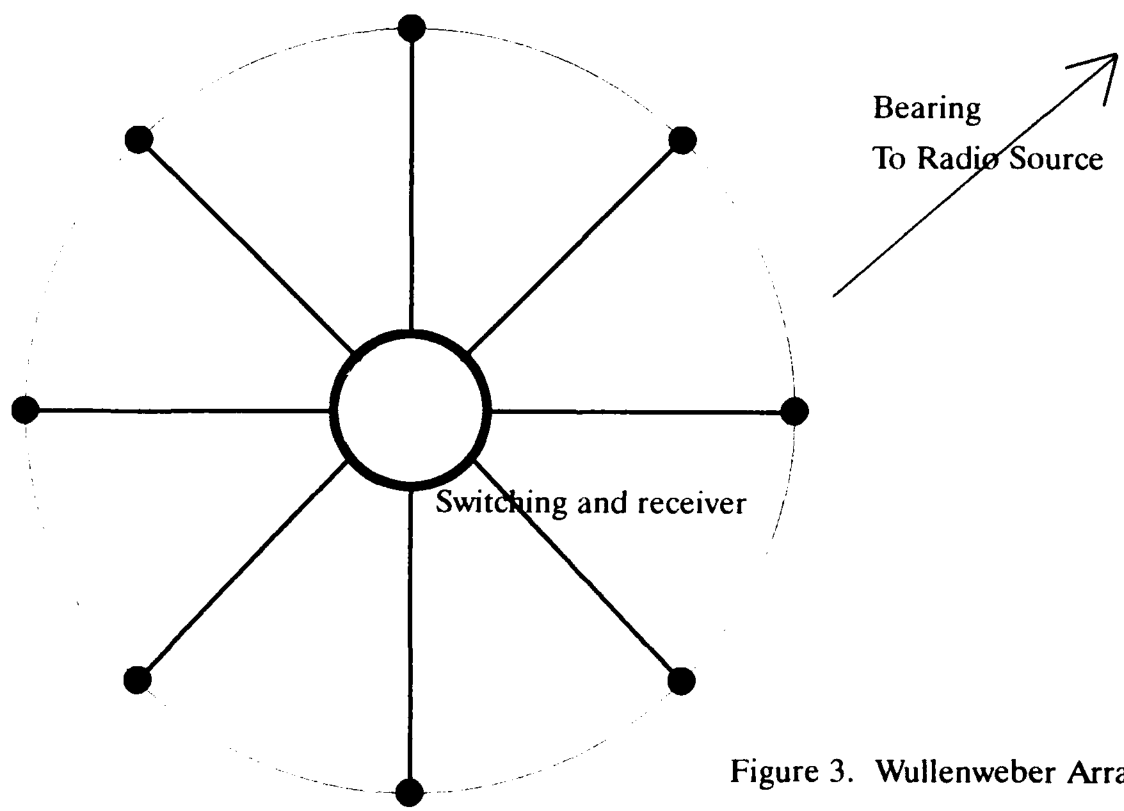

Figure 3. Wullenweber Array

The noise present in such a system causes a bearing mistake to be made when the difference between phase of the scanning signal as compared to the detected signal coming from the FM receiver. The noise at the detected output is white in nature. The same measurements made before still apply. The phase difference between the detected wave and the switching wave is found. As was shown this phase difference is proportional to the bearing azimuth. This difference is found by the comparison of zero crossings of both systems. Noise causes the exact time of the zero crossing of the value of $V_{det}(t)$ to be missed. The amount of noise is very low as long as signal levels are available which create full quieting in the FM system. The same analysis applied to the Adcock system also applies here and the same receiver data may be used. This means that the zero crossing will be missed by less than one degree of azimuth bearing.

Unlike the standard GPR problem where VHF and UHF frequencies are required to meet in ground limits of resolution, frequencies may be chosen in order to reduce the loss in the system and thereby increase the range of the system and at the same time increase the accuracy by improving the signal to noise ratio. The experimental system operated near 150 MHz,however a commercial version might operate near 50 MHz in orc ı to reduce losses which are present.

CONCLUSION

Instrumentation methods of trenchless technology have been reviewed. It is shown that for medium size boring systems GPR can be of use in both the locating and for providing information for the steering of the excavation. An analysis shows that doppler methods applied to a Wullenweber array will yield bearing results which would be acceptable for most trenchless excavation jobs.

PROBLEMS ENCOUNTERED AND ROLE FOR GPR IN CONCRETE TECHNOLOGY AND CORPS STRUCTURES ASSESSMENT

by

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Role of Radar for Corps Structures

Generally, no single technique will suffice to deliver 100 percent of the information desired from a nondestructive testing (NDT) assessment program on a concrete structure. Just as in the medical field where the physician must use numerous techniques and technologies to assess the health of a person, so it is with concrete structures; a suite of techniques is needed to access the health of a structure. Although NDT usually requires a suite of techniques for any given setting, ground penetrating radar (GPR) offers an important technique that is advancing the state of the art of NDT in concrete. The setting determines what technology is used. The setting includes the type of structure and environment (dimensions, depth of interest, presence of steel or water, type of deterioration, etc).

Cost-effective maintenance decisions can be made from NDT surveys. It enables managers to set adequate budgets and plan for future needs for maintenance, rehabilitation, or replacement. Cost of NDT assessment is always an important consideration for Corps of Engineer Districts that are charged with the responsibility for operation of the structure. Ideally, a survey should not cost more than 10 percent of the maximum anticipated maintenance or rehabilitation cost. In cases where enough information is known about the structure it may be possible to predict remaining service life.

The following is a list of the types of information that GPR has been used to obtain regarding concrete structures:

1. Moisture accumulation in deteriorated areas.
2. Chloride content of concrete.
3. Corrosion of reinforcing steel.
4. Concrete cover over reinforcement, position, and amount of steel reinforcement.

5. Internal cracking.
6. Lack of consolidation (honeycombing).
7. Foreign objects.
8. Delaminations in bridge decks.
9. Voids beneath concrete foundations.
10. Thickness of layer.

Radar has two features that make it ideal for surveying large structures. First, it is a non-contact technique unlike mechanical and acoustic techniques. Second, the pulses travel at the speed of light and, if suitable mechanical scanning equipment was available, one could scan a structure at highway speeds. The highway industry does in fact do that. Although it would be difficult to move at such speeds on a lock wall or stilling basin, survey times can certainly be improved with GPR by a factor of 10 or 20 over other existing techniques.

Desirable Features of Radar Unit for Corps Structures

The Corps has some structures that differ from other organizations. These structures require that special emphasis be placed on certain features of the measurement system if the technique is to be useful and cost effective. Some questions that relate to this effectiveness are: How quickly can you survey a structure? How quickly can you process the data and present the results? Will it work in the particular setting? How valid and what is the information that I will get? How much will it cost? Some of the important development features needed that will permit the implementation of radar on Corps structures are as follows:

1. There is a need to automatically measure and record the x-y cooordinates of a position every time the radar system records a signal, sometimes on a vertical surface. It needs to be capable of moving relatively rapidly, at least at a speed comparable that of the crane lowering the unit. A typical speed might be 10 to 20 ft per sec. Possibly, a radio control system could locate the position of the radar antenna by a technique of triangulation or trilateration as is done by geophysical survey systems. A transmitter and receiver could be located on the moving radar unit and a couple of radio transponders could be located at strategic positions on the structure. A

computer could automatically measure the time of arrivals and calculate a position. A similar system developed by the Waterways Experiment Station has been used for an above-water acoustic profiler for Corps structures. The lateral resolution of this system is about a foot but that can probably be improved.

2. Large amounts of data are involved when scanning the area of a lock wall or stilling basin. Surveying a lock wall that may be 600 ft long and 50 ft high will require a considerable volume of data to be stored in the computer. If measurements are taken on 3-in. centers then the horizontal distance will yield 2400 x-y coordinates and the vertical distance will yield 200 x-y coordinates. The total wall would yield 480,000 x-y coordinates. If each signal consists of 1024 data points per x-y coordinate then there will be 491,520,000 numbers. If the particular computer requires 4 bytes/number then that is a total of 1,966,080,000 bytes. The size of the hard disc would be 2 billion bytes (2 Gigabytes)! Initially it may only be possible to survey a small area corresponding to the size of the hard disc, process the data, and plot the results. The measurement, processing, and plotting of each smaller area can be continued until the full area is covered. The final picture of the structure's condition could be a mosaic of all the pieces.

3. Ideally, it would be instructive to plot an area of a lock wall or stilling basin, for example, with one picture. Although most radar signals are plotted as depth versus position it may be necessary to convert that depth plot to one number at a location that relates to the integrity or deterioration of the concrete. Each signal must be converted to some intensity value for that position and plotted as a grey scale or as colors on a profile plot. This should be an automated interpretation rather than a manual interpretation. The advantage of plotting information from a highway measurement is that the y-coordinate is constant (2 ft. from each side of highway) and one can simply plot the x-coordinate versus depth. Also a color plot would contain more information than a monochrome plot. It would be instructive for management and others unfamiliar with radar plots if a profile of the condition of the whole area could be plotted for the total depth of penetration.

4. Also, work needs to be done to correlate signal feature with the type and degree of deterioration. Physical models containing actual defects that

simulate various types of deterioration should be tested to determine the relationships of signal features with nature of defect. It is not as important to identify the type of deterioration as it is to recognize the presence and degree of the deterioration. Most types of deterioration cause physical discontinuties in the concrete; microcracks, delaminations, voids etc. Mathematical models can also be used to study the interaction of radar signals with various interfaces and then verified by experiment. Then a knowledge-based system is needed that will automatically interpret the meaning of the signal feature without requiring the use of an expert each time a measurement is made. This of course is not a simple undertaking.

5. An optimum frequency for concrete is 1 GHz. However, at this frequency the depth of penetration is only about 16 in. For wet concrete the depth of penetration is even less than 16 in. Actually, the radar wavelength at 1 GHz is longer than the ultrasonic wavelength at 200 kHz making ultrasonics presently better for resolution of defects. However the amount of data that can be gathered by radar in the same time frame can outweigh the resolution advantage for most settings. Large amounts of data can reveal subtle changes from display patterns that reveal deviations in properties from normal baseline variations. Large amounts of data yield better statistics on the average condition of the structure at a location or region.

INITIATION OF A NDT/GPR RESEARCH AND DEVELOPMENT EFFORT

BY
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ISD/WES

SECTION I UTILIZATION OF DIELECTRIC CONSTANT IN NONDESTRUCTIVE TESTING:

We are considering the use of radar technology to measure the magnitude and phase of the dielectric constant of concrete. The inverse method is a technique we will use to accomplish such an outcome. A network analyzer that is configured as a radar system is used by many to measure the dielectric constant in the laboratory and the field. The use of a network analyzer in this way is appealing because of its versatility, that is, its ability to simulate more than one type of radar. When an electromagnetic energy impinges upon a slab of concrete some of the energy will reflect from the illuminated area of the slab. Sometimes this reflected energy is called the radar signature of the scatterer (i.e. the illuminated area). It is in this signature the radar user finds the information regarding the illuminated area.

SECTION TWO RADAR APPLICATION AT THE STRUCTURES LABORATORY AT WATERWAYS EXPERIMENT STATION:

A monopulse radar is being used in the Structures Laboratory at Waterways Experiment Station. The efforts are being made to utilize it for nondestructive measurement and testing of concrete. This radar has successfully shown the location of reinforcing bars in a slab of concrete and an air gap between two slabs of concrete. The conclusive remark at this time is that the radar's resolution is vital in such a procedure. The polarity and value of the amplitude of the radar signature is an indication of abnormalities that exist in the concrete. Using the reflection coefficient argument from electromagnetic theory one can deduce whether the energy has propagated through adjacent media of different dielectric constants (e.g. from air to concrete or vis versa) or not. Radar resolution plays a significant role in this procedure. Suppose that a void filled with air exists in a slab of concrete, then it depends on the resolution of the radar whether this void is detected or not. If the void is detected, then the polarity change in the signature's amplitude is noticed and the void in the slab is declared. In particular we believe that radar range and azimuth resolutions are important parameters.

SECTION THREE PROCEDURES AND TECHNIQUES:

We are in the process of performing a set of tests in the laboratory and build a well defined data base for the benefit of utilizing radar in nondestructive testing and measurement. The resolution that a radar system can offer is considered important for nondestructive testing and measurement. We consider investigating the possibility of applying SAR technique to see if this leads to any improvements. Also, the application of a target recognition method will be considered for the same reason. Currently in the Structures Laboratory we have concrete slab models--voids in different sizes and shapes are present inside these models. We will conduct our investigations using these models. In addition, we are planning to establish measured data for the dielectric constant for concrete in different states.

USE OF GROUND-PENETRATING RADAR IN HYDROLOGIC, BRIDGE SCOUR, AND FRACTURE STUDIES

by John W. Lane, Jr., F.P. Haeni, and Gary Placzek

Ground-penetrating radar (GPR) methods have been used by the U.S. Geological Survey (USGS) since 1985 for hydrologic studies and since 1987 for bridge-scour studies. In addition, borehole radar, a specific type of GPR, has been used for fracture studies since 1990. These studies have been conducted on land, on ice, and on water bodies throughout the United States. Interpretation of GPR records is based on the location, configuration, amplitude, continuity, and termination of reflectors. Reflector characteristics have been related to the stratigraphic properties of sediments, type of bedrock, and location of fractures and other subsurface structural features.

In hydrologic studies, GPR methods have been used for qualitative and quantitative aquifer assessment, to identify lake sediments, to locate bedrock fractures, to delineate the lake/ground-water interface, to map the extent of ground-water contamination, to locate aquifer discharge zones into water bodies, and for water-table mapping. In studies that were conducted on land, penetration depth of the radar signal ranged from less than 1 ft (foot) in clay-rich sediments to more than 90 ft in clay-free sand and gravel. In studies conducted over water and ice, penetration depth of the radar signal changed with water quality. In very conductive water, the radar signal was attenuated completely in less than 3 ft of water. In less conductive water, the radar signal penetrated 70 ft of sand and gravel in 10 ft of water. Many of these GPR records had distinct water-bottom multiple reflections and diffraction patterns from point reflectors, such as boulders.

In bridge-scour studies, GPR methods combined with a laser-positioning system have been used to detect existing and infilled scour holes, exposed bridge foundations, rip-rap deposits, sunken debris, and buried stream channels. Subsurface stratigraphic features also have been determined, including thickness and extent of sand bars and location of the sediment/bedrock interface. The combination of a positioning system with GPR is essential in water-covered areas for digital processing of the radar data and to subsequently locate areas of interest that were interpreted from the processed data.

In fracture studies, borehole-radar methods have been used to detect individual fractures and fracture zones. Penetration distance of the radar signal ranged from 15 ft in shale to more than 100 ft in granite and schist. In addition, cross-hole attenuation and slowness tomography studies were conducted in several locations throughout the United States. The interpreted tomography results from the USGS fractured rock research site in Grafton County, New Hampshire indicate a fracture zone at a depth of 100 ft, which agrees with other borehole geophysical logs and the results of pump and tracer tests.

RECENT ADVANCES IN SUBSURFACE INTERFACE RADAR TECHNOLOGY

by
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ABSTRACT

The acceptance and use of Subsurface Interface Radar (SIR) has increased dramatically over the last five years. During this period, the number of SIR Systems in use worldwide has nearly quadrupled. New and increasingly diverse applications are putting demands on manufacturers to produce systems that can satisfy the growing range of resolution and penetration requirements. Systems must be more flexible yet simple to use and lower in cost.

The introduction of the SIR System-3 in 1986 by Geophysical Survey Systems, Inc. (GSSI) halved the cost of previous systems. Controls were simplified and the packaging more compact. In 1990, GSSI offered users complete flexibility with the SIR System-10. This system featured fully programmable digital controls, filters and four channel capabilities. The ability to operate up to four antennas simultaneously with different frequencies, setup parameters and transmitter and receiver geometries provided the user with a new dimension of data acquisition. In 1991, fiber optic cables were incorporated to improve the performance of all SIR Systems.

More recent advances in antenna and system design will be discussed. Since impulse radar systems transmit wide bandwidth signals, a variable frequency transmitter was developed. This was done to test the concept of varying the center frequency of a broad bandwidth antenna. Field measurements and results from two variable frequency antennas are presented. The first set of measurements were acquired from a bistatic antenna pair with a center frequency of 40 Mhz. Center frequencies ranging from 24 to 54 Mhz were attained. A second set of measurements were acquired from an antenna pair with a center frequency of 500 Mhz. Center frequencies of 500 and 900 Mhz were attained with this antenna. At 900 Mhz the variable frequency antenna had twenty five times more radiated power than the standard GSSI 900 Mhz antenna.

A new high speed multiple channel radar system will be described. This system will take advantage of the broad radiation patterns of impulse radar antennas to perform beam steering and focussing functions.

The Antenna Dilemma

Manufacturers of GPR equipment offer systems that accommodate antennas with different center frequencies. This approach allows end users a degree of flexibility to perform a greater number of tasks under a variety of field conditions. Each antenna has a fixed center frequency with a given range and resolution trade off. Center frequencies of different antennas from manufacturers typically increase by a factor of approximately two.

Frequency selection for a given survey is a function of range, resolution, field conditions and what is available to the end user. All too often the practitioner requires several antennas with different center frequencies to perform a survey or, an antenna with an intermediate center frequency other than what is available to them. Economic considerations may preclude the user from owning all the antennas that are available. There may be no ideal frequency antenna commercially available for a particular application requirement or site condition.

Variable Frequency Antennas

An antenna with a variable frequency capability could help solve many of these dilemmas. It could fill in the frequency gaps and facilitate the ability to tune the radar system to on-site conditions.

There are other advantages of applying variable frequency antennas to site investigations. Range and resolution compromises can be reduced. The identification of thin layers may be possible by sweeping through a continuous set of frequencies. The effect of subsurface heterogeneities (scatterers) may be reduced or enhanced. Lower frequencies can be transmitted from smaller and more portable antennas. More power at higher frequencies can be achieved. Any of these factors can impact the success or failure of a survey.

Current transmitter designs generate a fixed pulse. This output, when applied to a dipole antenna, will radiate an electromagnetic pulse with a wide bandwidth and radiation pattern. The center frequency of the radiated pulse is a function of the antenna dimensions. In order to change the frequency spectrum of the radiated pulse, it is necessary to use an antenna with different dimensions.

Since the radiated pulse consists of a wide band of frequencies, it seemed logical to assume that if the transmitter pulse-width could be varied, then the center frequency of the radiated pulse from a single antenna could also be varied.

Two variable frequency transmitters were developed to test this hypothesis. The design criteria called for a 2 to 1 frequency range. The frequency range of the two transmitters were from 20 to 40 Mhz and 500 Mhz to 1GHz. Bench tests of these transmitters yielded frequency measurements ranging from 22 to 47 Mhz and 500 to 900 Mhz. Figure 1 is an illustration of four waveforms generated by the lower frequency transmitter. The frequencies of the waveforms from top to bottom are 47, 40, 30 and 22 Mhz respectively.

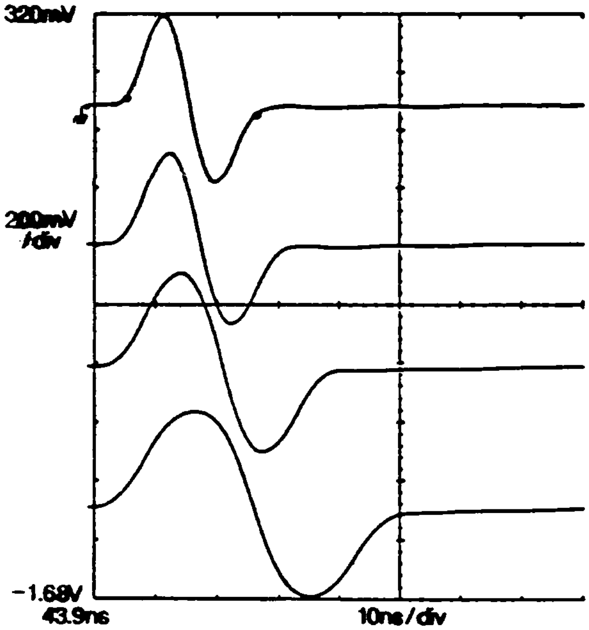

Figure 1: Waveforms generated by a variable frequency transmitter.

Additional testing with current antennas demonstrated the need for an antenna design that would provide the maximum benefit from the variable frequency transmitters. Two antennas were designed and built to operate within the frequency ranges of the transmitters.

Low Frequency Measurements

A wide bandwidth dipole antenna was used to test the low variable frequency transmitter. The approximate center frequency of this antenna coupled to the ground surface was 40 Mhz. Figures 2a and 2b are identical profiles scanned with transmitter frequencies of 22 and 47 Mhz. The range was 1000 ns. The 22 Mhz data (Figure 2a) showed the water table and bedrock interfaces very clearly. The 47 Mhz data (Figure 2b) provided greater detail of the overburden materials but the bedrock and water table reflectors were more ambiguous.

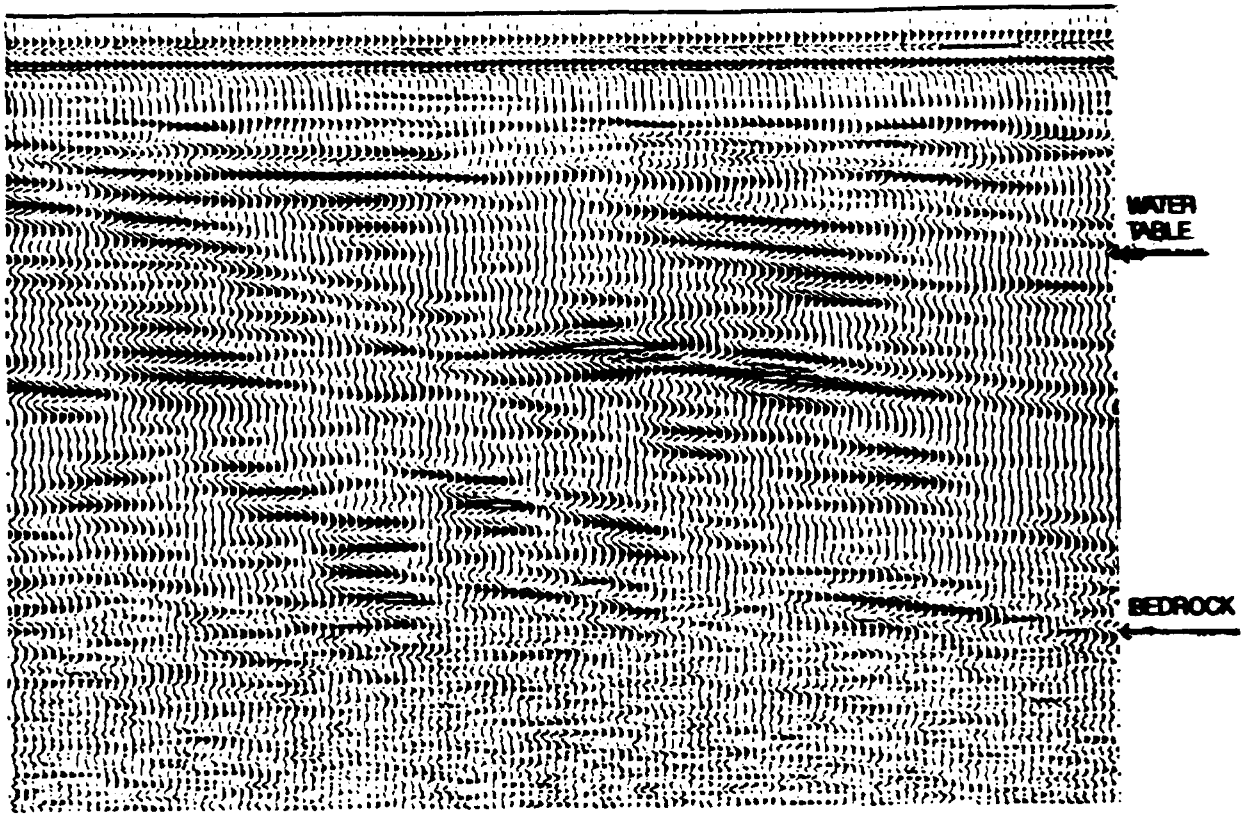

Figure 2a: 1000 ns radar profile with a transmitter frequency of 22 Mhz.

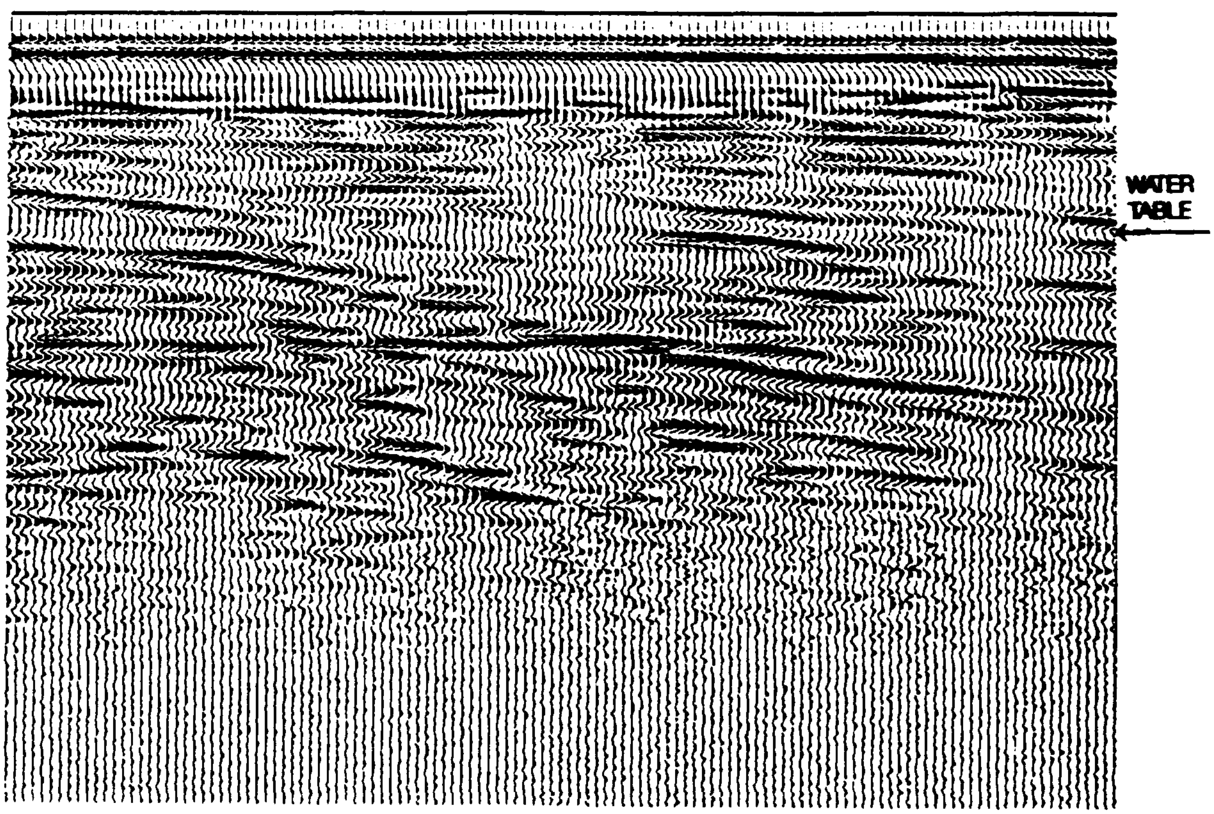

Figure 2b: 1000 ns radar profile with a transmitter frequency of 47 Mhz.

Frequency spectrums of these profiles (Figures 3a and 3b) clearly showed the shift to higher frequencies at the 47 Mhz setting (Figure 3b). The minimum and maximum center frequencies derived from this data were 24 and 54 Mhz respectively.

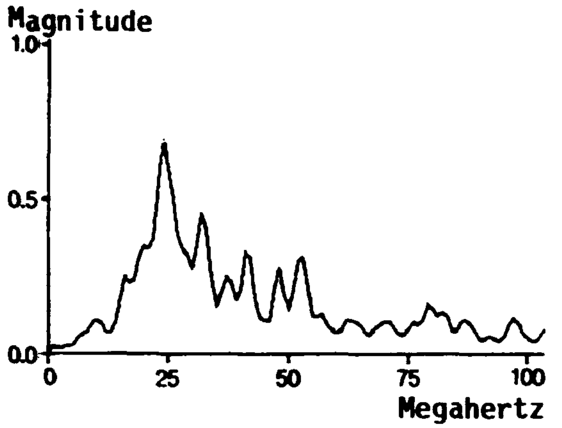

Figure 3a: Frequency spectrum from data in Figure 2a.

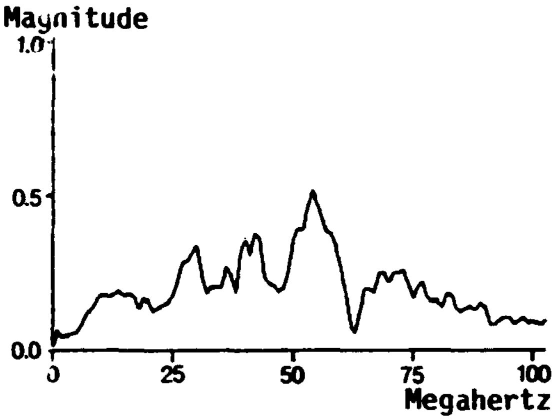

Figure 3b: Frequency spectrum from data in Figure 2b.

High Frequency Measurements

A higher frequency wide bandwidth dipole antennas was used with the high frequency variable transmitter. The wide bandwidth antenna was designed to operate in this frequency range. A test area at GSSI with known buried reflectors was scanned.

Figures 4a and 4b are frequency spectrums of data at the 500 and 900 Mhz settings of the variable frequency transmitter. Figure 4c is the frequency spectrum of a standard GSSI 500 Mhz antenna and Figure 4d the frequency spectrum of a standard GSSI 900 Mhz antenna. The spectrums of Figures 4a and 4c (500 Mhz) were quite similar. The spectrums of Figures 4b and 4d (900 Mhz) showed the higher frequency content of the received signal. Note the bandwidth of the variable frequency antenna at the maximum frequency setting (Figure 4b) was much wider than the other examples.

Of great interest on these tests was the greater radiated power of the variable frequency antenna at the 900 Mhz setting versus the standard 900 Mhz antenna. The radiated power increased in this case by a factor of twenty five.

MULTIPLE CHANNEL RADAR SYSTEM

The SIR System-10 was the first GPR system to allow the simultaneous operation of up to four antennas or antenna pairs. Each channel can have similar or different frequency antennas. Set-up parameters on each channel such as signal position, range, gains and filters can be individually programmed.

Four software channels managed the input from single or multiple (up to four) antennas or antenna pairs. Data are processed, displayed and stored sequentially on a scan by scan basis from a single radar board.

Although this system offered a new dimension and flexibility for GPR practitioners, multiple antenna operation limited the speed of the system. New applications such as inspecting roadbed conditions required faster data acquisition speeds. In addition, the very nature of multiple antenna operation resulted in demands for beam focusing and steering functions from antenna arrays.

A new prototype multiple channel radar system was developed to increase system

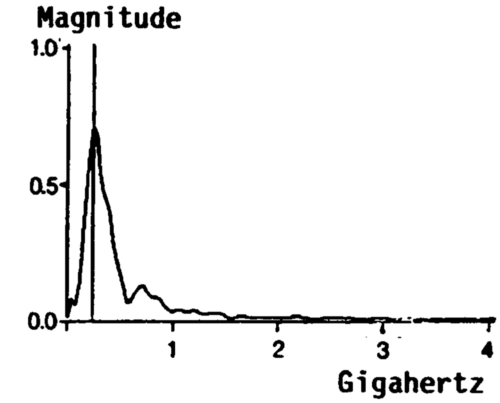

Figure 4a: Frequency spectrum of the variable frequency antenna at 500 Mhz

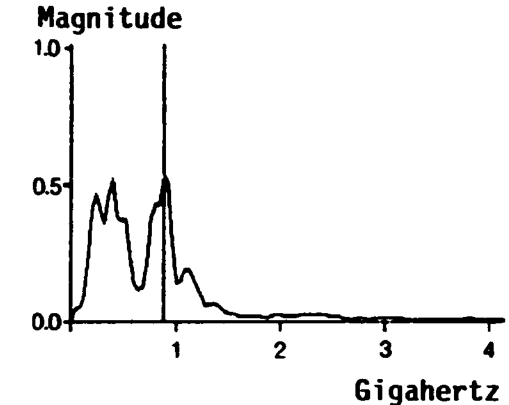

Figure 4b: Frequency spectrum of the variable frequency antenna at 900 Mhz

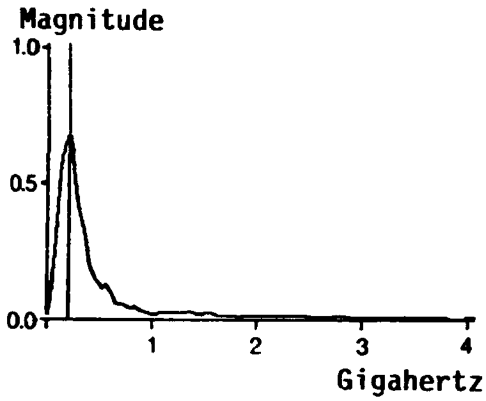

Figure 4c: Frequency spectrum of a standard GSSI 500 Mhz antenna

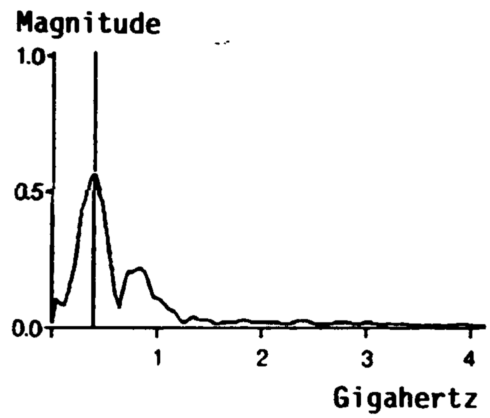

Figure 4d: Frequency spectrum of a standard GSSI 900 Mhz antenna

speed and the capability to form these antenna arrays. Instead of using one radar board as in the SIR-10, four radar boards were incorporated in the new system. Each channel can operate with its own radar board.

The system can be used in two modes of operation with five antennas or antenna pairs. In the first case, all antennas are fired sequentially to produce five individual scans. The five scans can be used to increase areal coverage in a single pass or stacked together to improve system performance. The second mode of operation involves firing all the antennas simultaneously to form a beam. Time shifters can then be individually programmed on each channel to form beam patterns. The purpose of the time shifters is to delay the transmitted or received signal on individual channels. By doing so, and by placing the antennas in particular geometric patterns, it is possible to produce a composite radar signal that can be steered or focused. In this mode of operation it is possible to focus or steer the composite beam pattern of the antennas. Four beam steering and focusing functions are described.

Previous discussions centered around the exploitation of the wide bandwidth produced by the antennas in pulsed GPR systems. Since these antennas also produce broad radiation patterns, the use of time shifters allow the radar system to direct the radiation pattern of the antennas. Four beam steering and focussing functions are possible with this system.

The first is to focus on a point and sweep across a line containing that point. In this case, transmit antenna time delays are selected by the end-user so that the signals all converge on a point at a desired distance. The degree of focusing is a function of the spacing between individual antennas. This is illustrated with polar plots of the beam patterns in Figures 5a and 5b. In Figure 5a the

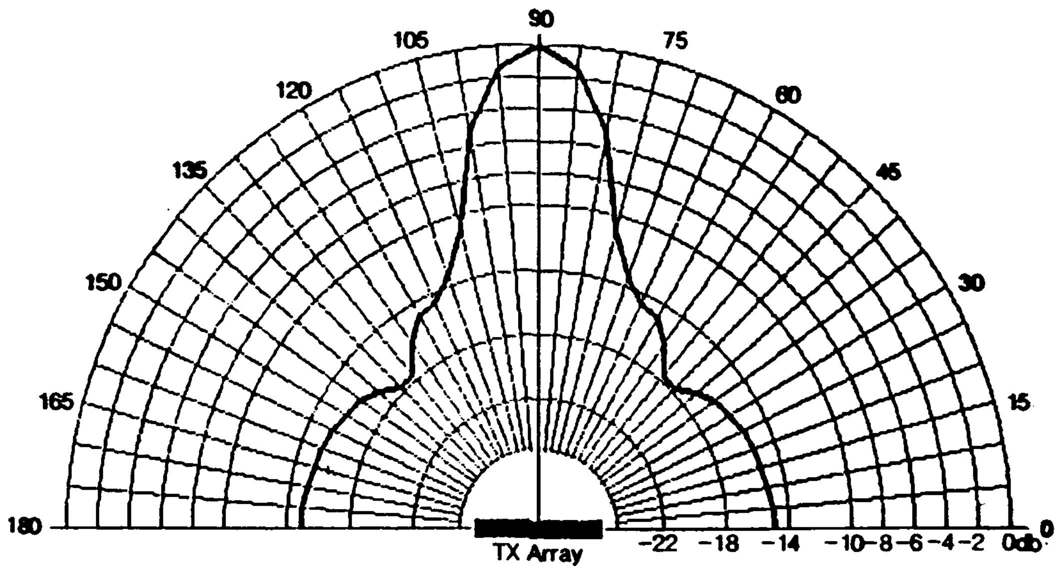

Figure 5a: Polar plot of radiation pattern from a 5 antenna array with a 50 cm antenna separation focussed on a point

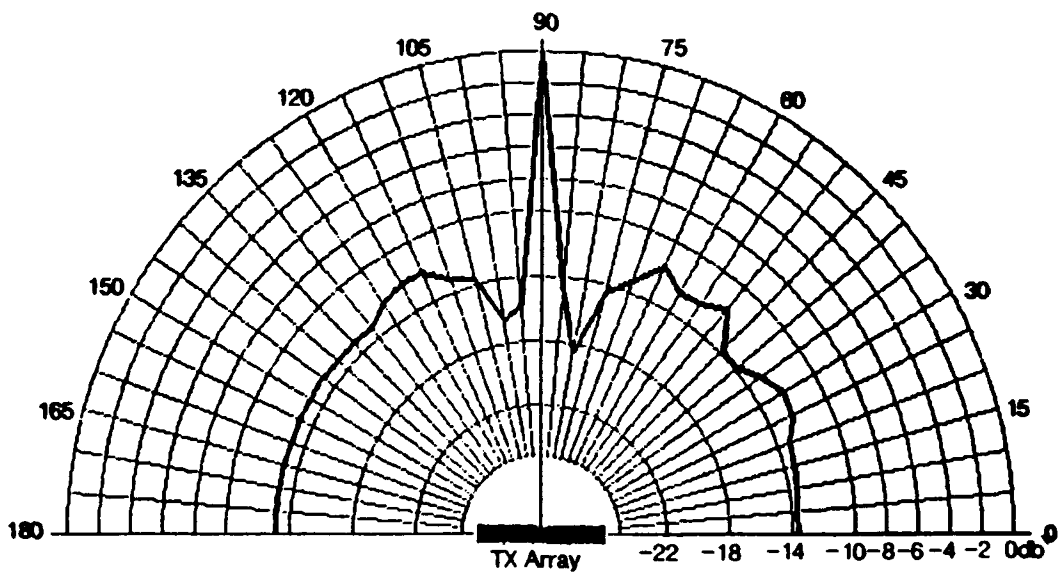

Figure 5b: Polar plot of radiation pattern from a 5 antenna array with a 200 cm antenna separation focussed on a point

antennas had a separation of 50 cm. The antenna separation for Figure 5b was 200 cm. The wider the antenna spacing, the greater the focusing effect. The second function is to focus on a point and sweep across an arc containing that point. As before, the antenna delays are programmed by the practitioner to converge at a defined distance. The degree of focusing is a function of the antenna spacing. The third function is to form five parallel beams along a line and sweep across it. The fourth function is to sweep across an arc with five parallel beams. This is accomplished by aiming the center antenna beam so that it is perpendicular to the arc. The other antenna beams would then be configured parallel to the central one with individual time delays that are a function of the desired radius. It is then possible to sweep the five parallel beams across an arc.

Data is stored on an internal 5 gigabyte tape drive for post processing. The system contains seven digital signal processors (DSP) and an 80386 computer with an 80387 math coprocessor. Parallel post acquisition processing on the five channel data will be accomplished by utilizing this hardware. Each channel will be assigned its own processor.

SUMMARY

The most difficult task in any GPR study is the interpretation of the data. Data interpretation can be improved only if the quality of the images produced by a GPR system can also be improved.

Variable frequency antennas offer the possibility of tuning the radar system to specific application requirements and site conditions. Problems identifying thin layers may be overcome by adjusting the wavelength of the radar signal to an optimum value at a given site. Major changes in subsurface conditions such as the depth to the water table or bedrock may be easier to recognize when the optimum frequency is found. Better impedance matching of the antenna to the ground surface will improve system performance.

High quality three dimensional images of subsurface targets can only be produced when the system can view the targets in three dimensions. This capability may be realized with beam steering functions.

Additional penetration performance can be attained by stacking data received from multiple antennas. These hardware improvements, when coupled with more advanced signal processing software, will further advance the emerging applications of ground penetrating radar.

AN OVERVIEW OF THE

pulseEKKO™ GROUND PENETRATING RADAR TECHNOLOGY

A.P.Annan and S.W. Cosway

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5566 Tomken Road
Mississauga, Ontario, Canada
L4W 1P4

The application of ground penetrating radar requires the user to address four subject areas, namely, instrumentation, methodology, data processing and presentation, and interpretation. The pulseEKKO family of ground penetrating radar systems have been designed to facilitate addressing of all four of these issues. All aspects of the pulseEKKO systems have been designed and developed because of the need to address real world applications. As a result, flexibility and simplicity are at the heart of all of the systems. In the following a brief overview of the systems characteristics and associated data display and processing software are provided.

The first commercial Sensors & Software Inc. system was the pulseEKKO IV. As the number implies this was the fourth in a series of systems which were developed over a period of about 10 years. The pulseEKKO IV is a modular instrument which uses any IBM compatible PC as its control master. The unit consists of a console which provides the interface between a PC and the active radio frequency components of the system. The radio frequency components, i.e., the transmitter and receiver electronics are interfaced to the console via a fibre optics links. The use of fibre optics links is a key ingredient in achieving high fidelity particularly at low frequencies of operation. All of the modules including the console and the transmitter and receiver electronics are battery powered. As a result, the instrument is quite compact and extremely portable. The use of lightweight plastics and composite materials make the unit extremely robust.

The pulseEKKO IV instrument was primarily developed for geological sounding applications. The frequency of operation commercially available ranges from 12.5 through 200 MHz. The system has a bistatic arrangement so that the antennas can be deployed in a wide variety of manners. This bistatic arrangement makes it very easy to carry out CMP/WARR velocity soundings and transillumination experiments for tomographic applications in addition to optimizing the transmitter and receiver separations for the routine common offset reflection profiling mode of operation. The system like all commercial ground penetrating radar systems uses repetitive waveform sampling to acquire the data. The advantage of the pulseEKKO system is that it provides for user control over stacking so that multiple repetition of the signals can be averaged at a site before moving the transducers. For operations in rough terrain or for work in tunnels and other hard to get at areas the ability to be able to acquire data on demand and have the system remain passive until additional data acquisition is required is a key feature.

The second system in the pulseEKKO family is the pulseEKKO 1000. The pulseEKKO 1000 is the complement to the pulseEKKO IV. The pulseEKKO 1000 is designed to operate over a frequency range from 200 to 1000 MHz. As with the pulseEKKO IV this system is bistatic with modular design and interchangeable antennas to provide maximal flexibility. All operational features of the pulseEKKO IV are also present in the pulseEKKO 1000. Again portability and robustness as well as simplicity of operation are integral to the pulseEKKO 1000 design. In fact the engineers have gone so far as to totally remove any switches from the pulseEKKO 1000. There are no user knobs or adjustable switches on the hardware.

The pulseEKKO systems are all designed to run with an IBM compatible PC as the master unit. All pulseEKKO systems come complete with an integrated software package which allows the user to manage all aspects of the systems capabilities. A series of modules allow for operation, acquisition and storage of data. A second module allows the user to plot and display the data in a variety of formats. The third module provides editing and manipulation of data sets in order that the final report quality product can be made up with annotations and labels according the field operations.

A whole variety of additional capabilities are part of the modular software package and include the ability to generate synthetic radargrams, to carry out velocity analysis on CMP/WARR soundings, to assess the utility of radar for a particular application by solving the radar range equation iteratively, and to provide a variety of bandpass filters on the data. In addition, the standard software permits the user to export the data in SEG-Y or ASCII formats so that processing with any commercially available seismic software package can be carried out. Users routinely use the MICROMAX or VISTA package as well as a variety of other seismic packages for data processing.

Sensors & Software Inc. also provides user training and a whole spectrum of technical note and case history documents to assist users in learning about radar and understanding the procedures for data interpretation. The area of data interpretation and enhanced processing is still a very new one and major advances are being made in this area all the time. Sensors & Software Inc. works hard with its customers and the scientific community to assist in augmenting the information base available to new users in the field.

Airborne, Borehole and Surface Ground Penetrating Radar: Measurement, Processing and Modelling

by

Gary R. Olhoeft
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Denver, CO 80225-0046
(303) 236-1302 of
(303) 236-1425 fx

The U.S. Geological Survey applies ground penetrating radar to many problems. In the course of these activities, commercial radar equipment is used as delivered, modified for special needs, or new equipment is designed and built from scratch. Examples of these latter two are construction of borehole radar antennas to fit in 2-inch PVC water wells for hole-to-hole tomography and construction of all-digital radiofrequency gigasample/second systems for airborne ice sounding. For many problems, the solution is available in the raw radar data. However, for some problems, computer processing of the radar data is required to remove artifacts of the data acquisition process, reduce environmental noise, or present a geometrically correct cross-section. In other cases, the problem may only be solved (or the quality of the data confirmed) by computer modelling of the radar data. The USGS has developed an extensive set of programs for computer processing and modelling of airborne, borehole, and surface radar data. These measurement, processing and modelling tools are backed up by laboratory investigations of electrical properties. Collectively, these tools have been applied to a wide variety of problems, including exploration of the moon and Mars, resource assessments, void and tunnel detection, Arctic and Antarctic ice budgets, fracture mapping, and a wide variety of geotechnical and environmental problems.

GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT

FIELD DEMONSTRATIONS AND EXHIBITS

Two manufacturers of GPR systems displayed exhibits at the Workshop: Geophysical Survey Systems, Inc. (GSSI), North Salem, New Hampshire; Systems and Software, Inc. (SSI), Mississauga, Ontario, Canada. Representatives of these GPR manufacturers also made technical presentions on current research and development activities and current equipment capabilities. A highlight of the workshop was field demonstration of two GPR systems (the GSSI SIR System 10 and the SSI pulseEKKO™ IV). The two GPR systems were demonstrated at two sites. One site was in a large hangar which contained two types of concrete test sections: (1) 5 inch, 10 inch, and 15 inch portland cement concrete sections over soil, with reinforcing rods about 1 inch above the soil; (2) sections consisting of 2 inch asphaltic concrete over 6 inch, 10 inch, 12 inch, 14 inch, and 18 inch gravel base course, over compacted clay. The second site was the WES Environmental Geophysics Training Facility, which was developed specifically as a field training site for short courses but with a potential for research and development activities.

The demonstrations were not designed to be exhaustive investigations of the two sites, but were primarily intended to display and explain epuipment operation and features. The following two pages contains pictures of the field demonstrations. Also, the demonstrations illustrated the appearance of GPR records over representative subsurface features. The GSSI demonstration consisted of displaying the GPR records on a color monitor. The SSI demonstration consisted of displaying the GPR records on a laptop computer screen. SSI also recorded the data records. The Case Study which follows, prepared and submitted by SSI subsequent to the Workshop, documents the results of the SSI demonstration at the Environmental Geophysics Training Facility.

GSSI demonstration over concrete test section, 1GHz antenna

GSSI demonstration at Env. Geoph. Training Facility, 500 MHz antenna

SSI demo over concrete test section,
200 MHz antenna

SSI demo at Env. Geoph. Training
Facility, 200 MHz antenna

CASE STUDY

TEST RESULTS FROM THE

GOVERNMENT USERS WORKSHOP ON GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT.

US ARMY CORPS OF ENGINEERS
WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

MARCH 1992

Systems and Software, Inc.
Mississauga, Ontario, Canada

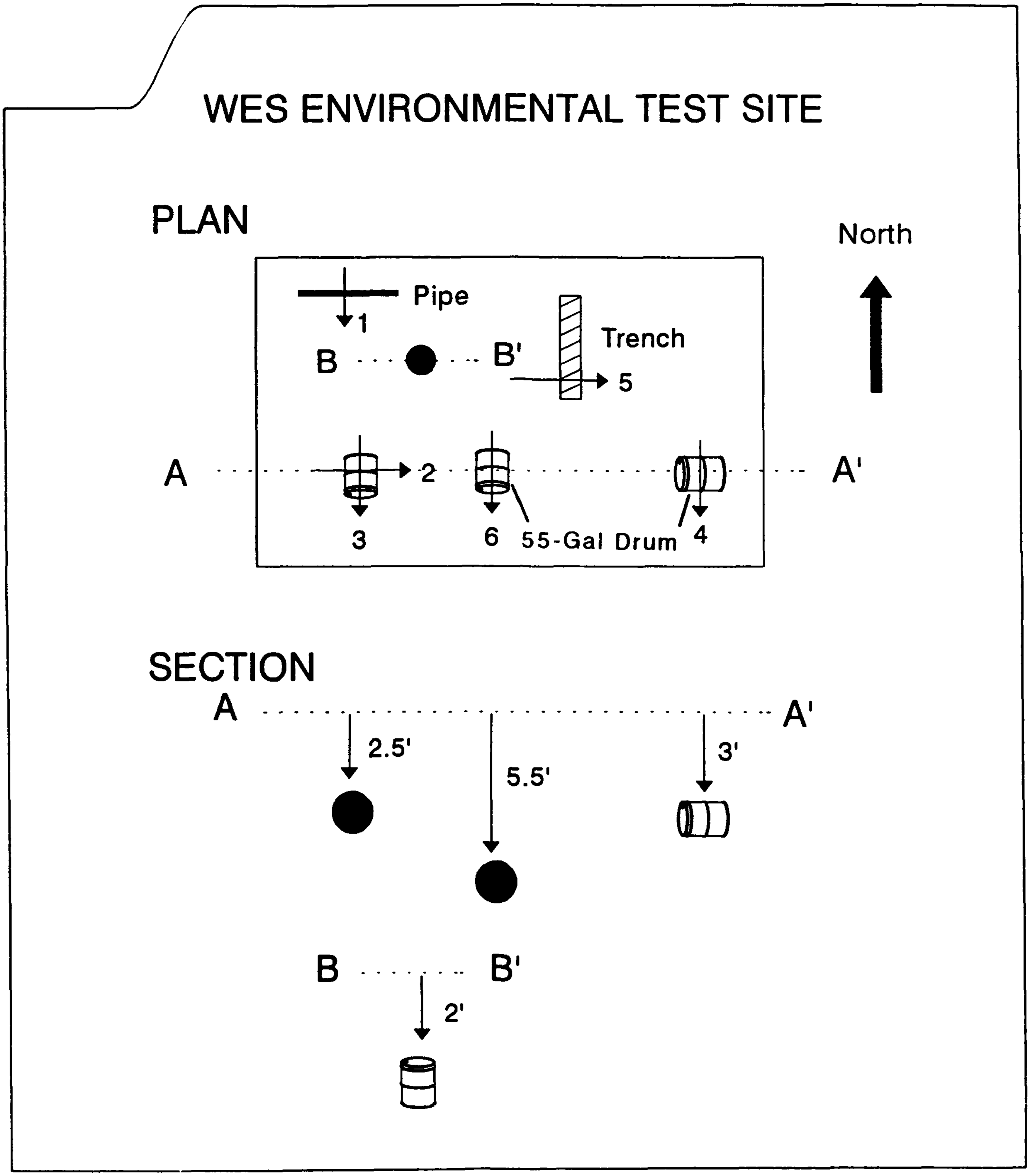
The following data were collected at the US Army Corps of Engineers Waterways Experiment Station (WES) located in Vicksburg, Mississippi. The data were collected as part of the Government Users Workshop on Ground Penetrating Radar Applications and Equipment held in March 1992.

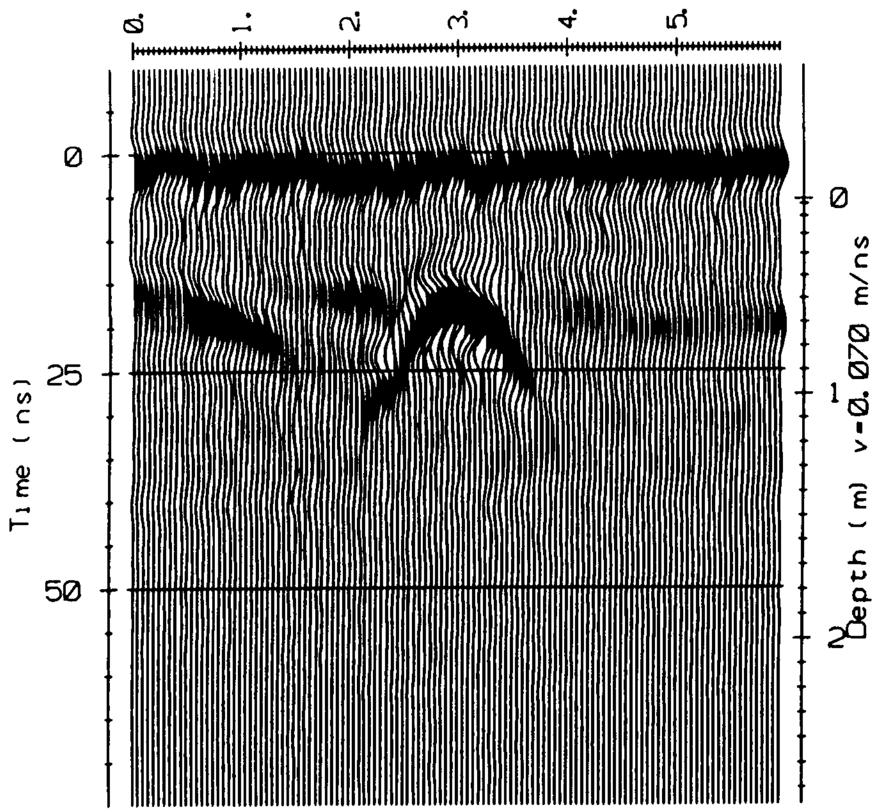
The WES test facility for environmental geophysics training consists of a field in which a number of know targets are buried. Enclosed is a map of these target locations.

The data were collected using the **pulseEKKO IV** ground penetrating radar system using a 200 MHz antenna. All the plotting and data collection parameters can be found on the header page located beside each plot.

A total of 6 lines were surveyed. These files are labeled as WES1 thru WES6 and their location can be found on the site map. The anomalies appear as hyperbolas on the sections.

No attempt was made to optimize the system configuration for the site. Data presented are as obtained while profiling during site orientation and demonstration to workshop attendees. Not all targets were surveyed nor were alternate operating frequencies or antenna polarizations tested to improve depth of penetration.


WES ENVIRONMENTAL TEST SITE
PLAN
North
Pipe
1
Trench
B
B'
5
A
2
A'
3
6
55-Gal Drum
4
SECTION
A
A'
2.5'
5.5'
3'
B
B'
2'




```
PulseEKKO IV Data Sheet

DATA FILE #1 PARAMETERS:
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   M0036
   WES  TEST SITE TARGET A1
   Buried pipe with profile from N to S. Pipe at about 3m.
   27/03/92
   NUMBER OF TRACES    = 121
   NUMBER OF PTS/TRC   = 125
   TIMEZERO AT POINT   = 28
   TOTAL TIME WINDOW   = 100
   STARTING POSITION   = 0.000000
   FINAL POSITION      = 6.000000
   STEP SIZE USED      = 0.050000
   POSITION UNITS      = metres
   NOMINAL FREQUENCY   = 200.000000
   ANTENNA SEPARATION  = 0.500000
   PULSER VOLTAGE (V)  = 400
   NUMBER OF STACKS    = 64
   SURVEY MODE         = Reflection

PROCESSING SELECTED:
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   Points Stacking   : 5
   Trace Differencing: N
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     Attenuatn: 5.000 dB/m
     Amount   : 10 Maximum
   Selection  : Time = -10 to 75  ns
                Trace = 1 to 120
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PLOT LAYOUT PARAMETERS:
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Profile 1

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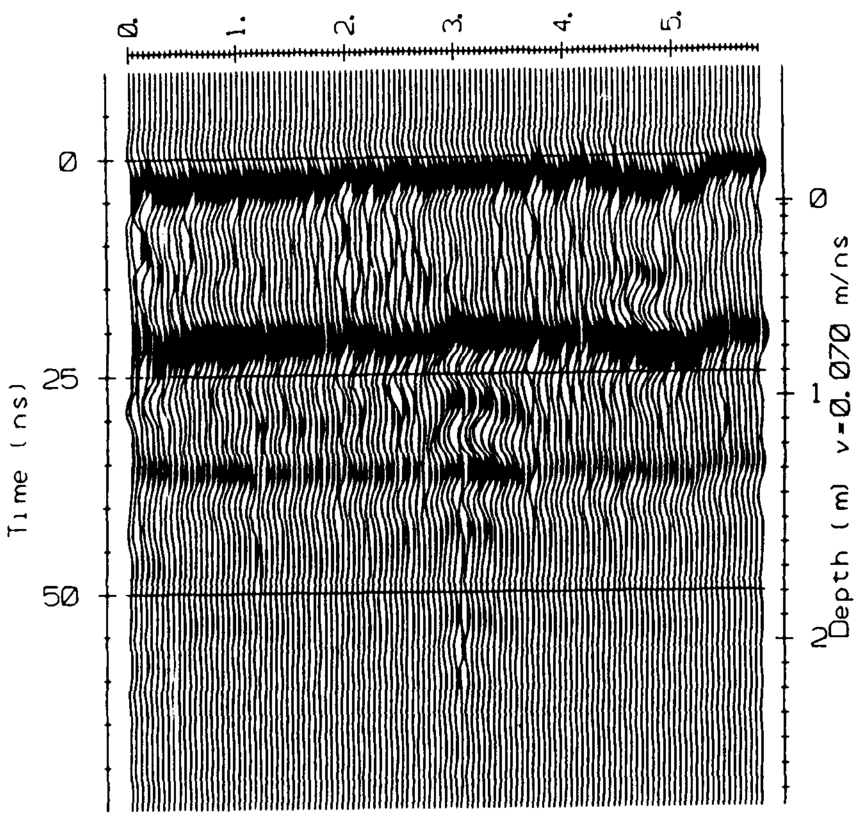


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PulseEKKO IV Data Sheet

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   5254
   WES  TEST SITE 1
   PIPES
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   NUMBER OF TRACES    = 117
   NUMBER OF PTS/TRC   = 250
   TIMEZERO AT POINT   = 15
   TOTAL TIME WINDOW   = 200
   STARTING POSITION   = 0.000000
   FINAL POSITION      = 5.800000
   STEP SIZE USED      = 0.050000
   POSITION UNITS      = metres
   NOMINAL FREQUENCY   = 200.000000
   ANTENNA SEPARATION  = 0.500000
   PULSER VOLTAGE (V)  = 400
   NUMBER OF STACKS    = 64
   SURVEY MODE         = Reflection

PROCESSING SELECTED:
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   Points Stacking   : 5
   Trace Differencing: N
   Gain Type  : SEC
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     Attenuatn: 10.000 dB/m
     Amount   : 20 Maximum
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   Trace Width       : 0.120"
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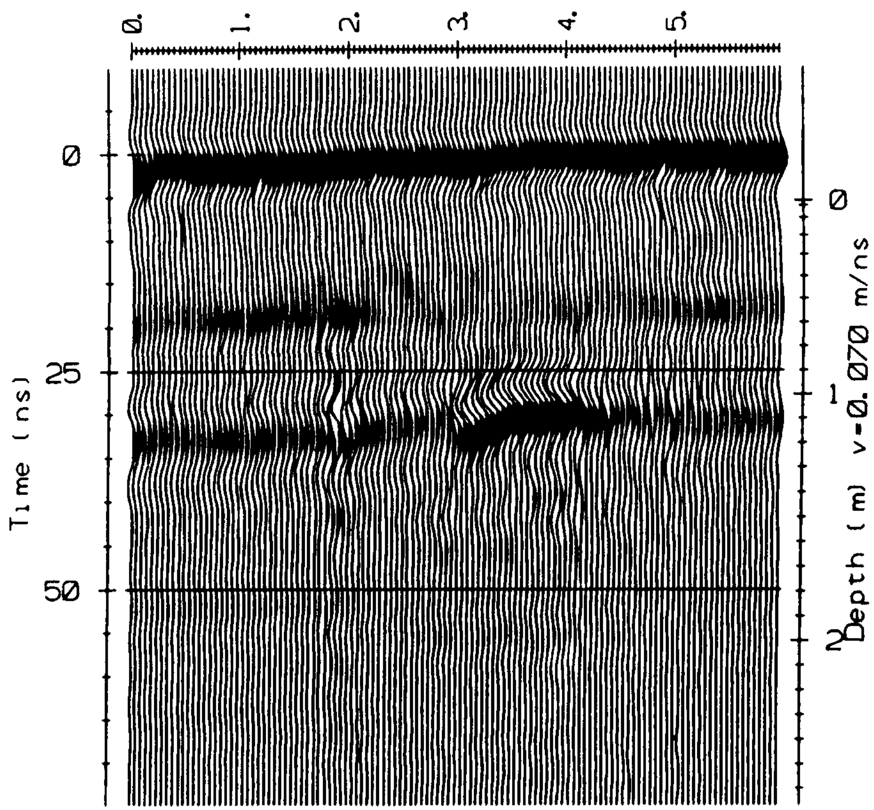


```
PulseEKKO IV Data Sheet

DATA FILE #1 PARAMETERS:
   Data File  = C:\WES\wes3.hd
   5254
   WES  TEST SITE 1
   barell 1
   26/03/92
   NUMBER OF TRACES    = 120
   NUMBER OF PTS/TRC   = 250
   TIMEZERO AT POINT   = 26
   TOTAL TIME WINDOW   = 200
   STARTING POSITION   = 0.000000
   FINAL POSITION      = 5.950000
   STEP SIZE USED      = 0.050000
   POSITION UNITS      = metres
   NOMINAL FREQUENCY   = 200.000000
   ANTENNA SEPARATION  = 0.500000
   PULSER VOLTAGE (V)  = 400
   NUMBER OF STACKS    = 64
   SURVEY MODE         = Reflection

PROCESSING SELECTED:
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   Points Stacking    : 5
   Trace Differencing: N
   Gain Type  : SEC
     Velocity : 0.070 m/ns
     Attenuatn: 10.000 dB/m
     Amount   : 20 Maximum
   Selection  : Time = -10 to 75  ns
                Trace = 1 to 120
   Picture Id : 04/09/92-14:21:33

PLOT LAYOUT PARAMETERS:
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   Trace Width        : 0.120"
   Trace Position     : 1.500" to 5.500"
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Profile 3

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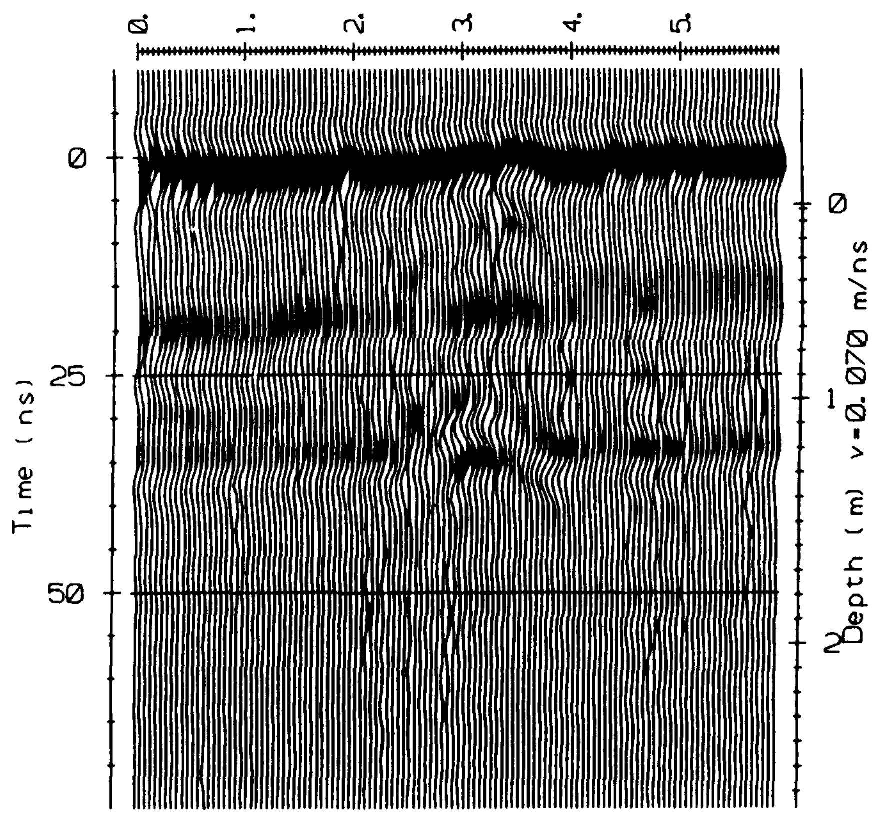


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PulseEKKO IV Data Sheet

DATA FILE #1 PARAMETERS:
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   5254
   WES  TEST SITE 1
   barell 1
   26/03/92
   NUMBER OF TRACES     = 119
   NUMBER OF PTS/TRC    = 250
   TIMEZERO AT POINT    = 17
   TOTAL TIME WINDOW    = 200
   STARTING POSITION    = 0.000000
   FINAL POSITION       = 5.900000
   STEP SIZE USED       = 0.050000
   POSITION UNITS       = metres
   NOMINAL FREQUENCY    = 200.000000
   ANTENNA SEPARATION   = 0.500000
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   NUMBER OF STACKS     = 64
   SURVEY MODE          = Reflection

PROCESSING SELECTED:
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   Trace Differencing: N
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     Attenuatn: 10.000 dB/m
     Amount   : 20 Maximum
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                Trace = 1 to 120
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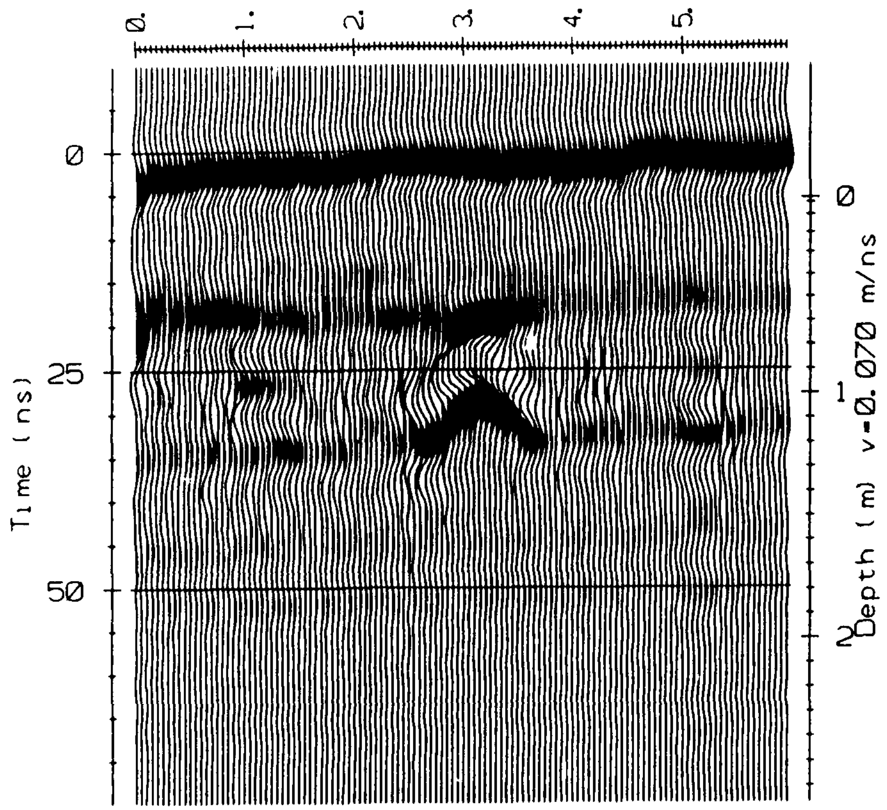
Profile 4




```
PulseEKKO IV Data Sheet

DATA FILE #1 PARAMETERS:
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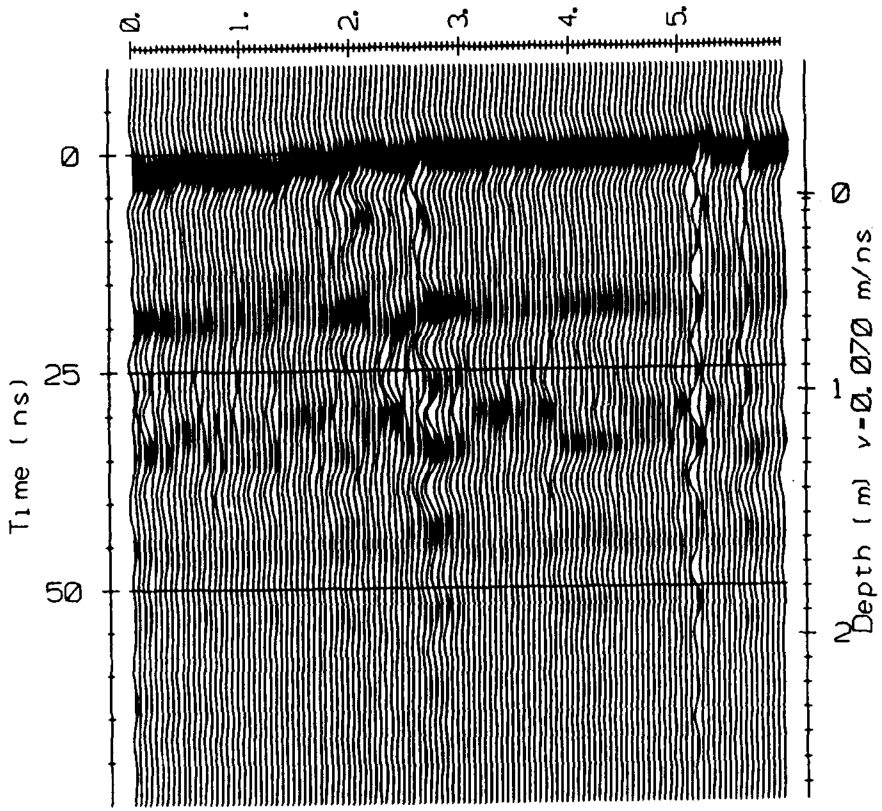
   M0036
   WES  TEST SITE  TARGET A5 (Sand filled trench)
   Profile from W to E with trench at about 3m.
   27/03/92
   NUMBER OF TRACES    = 143
   NUMBER OF PTS/TRC   = 125
   TIMEZERO AT POINT   = 25
   TOTAL TIME WINDOW   = 100
   STARTING POSITION   = 0.000000
   FINAL POSITION      = 7.100000
   STEP SIZE USED      = 0.050000
   POSITION UNITS      = metres
   NOMINAL FREQUENCY   = 200.000000
   ANTENNA SEPARATION  = 0.500000
   PULSER VOLTAGE (V)  = 400
   NUMBER OF STACKS    = 64
   SURVEY MODE         = Reflection

PROCESSING SELECTED:
   Trace Stacking    : 1
   Points Stacking   : 5
   Trace Differencing: N
   Gain Type  : SEC
     Velocity : 0.070 m/ns
     Attenuatn: 10.000 dB/m
     Amount   : 20 Maximum
   Selection  : Time = -10 to 75  ns
                Trace = 1 to 120
   Picture Id : 04/09/92-14:40:13

PLOT LAYOUT PARAMETERS:
   Trace Spacing      : 0.030"
   Trace Width        : 0.120"
   Trace Position     : 1.500" to 5.500"
   Left/Right Margin  : 0.000" / 0.000"
   Border Size        : 0.000"
   Page Length/Width  : 10.000" / 7.000"
   Printer Name       : HP LaserJet II 300dpi
```

Profile 5

04/09/92 14:40:13




```
PulseEKKO IV Data Sheet

DATA FILE #1 PARAMETERS:
   Data File  = C:\WES\wes6.hd
   M0036
   WES  TEST SITE TARGET A3 (Horizontal barrel at 5.5' depth)
   Profile from N to S (The same as previous day as best we can gu
   27/03/92
   NUMBER OF TRACES    = 127
   NUMBER OF PTS/TRC   = 125
   TIMEZERO AT POINT   = 25
   TOTAL TIME WINDOW   = 100
   STARTING POSITION   = 0.000000
   FINAL POSITION      = 6.300000
   STEP SIZE USED      = 0.050000
   POSITION UNITS      = metres
   NOMINAL FREQUENCY   = 200.000000
   ANTENNA SEPARATION  = 0.500000
   PULSER VOLTAGE (V)  = 400
   NUMBER OF STACKS    = 64
   SURVEY MODE         = Reflection

PROCESSING SELECTED:
   Trace Stacking    : 1
   Points Stacking   : 5
   Trace Differencing: N
   Gain Type   : SEC
     Velocity : 0.070 m/ns
     Attenuatn: 10.000 dB/m
     Amount   : 20 Maximum
   Selection  : Time = -10 to 75  ns
                Trace = 1 to 120
   Picture Id : 04/10/92-07:40:20

PLOT LAYOUT PARAMETERS:
   Trace Spacing      : 0.030"
   Trace Width        : 0.120"
   Trace Position     : 1.500" to 5.500"
   Left/Right Margin  : 0.000" / 0.000"
   Border Size        : 0.000"
   Page Length/Width  : 10.000" / 7.000"
   Printer Name       : HP LaserJet II 300dpi
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Profile 6

04/10/92-07:40:20

GOVERNMENT USERS WORKSHOP
ON
GROUND PENETRATING RADAR APPLICATIONS AND EQUIPMENT

PANEL DISCUSSION

The final event of the Workshop was a panel discussion, with Messrs. Butler (Moderator), Olhoeft, Doolittle, Bevan, Annan, and Fenner participating. Discussion format consisted of a series of questions posed to the panel by the Moderator. The questions are listed below, followed by any substantive comments by Panel members (comments are paraphrased and not direct quotes).

Question 1: Is there a need for formal or informal government standards or guidelines for QA/QC for GPR practice? If so, what are possible venues for implementation?

Fenner--Guides or guidelines are needed, not standards. ASTM is presently working on geophysical survey guidelines.

Olhoeft--We need standards. Having standards helps not only with QA/QC but legally; a survey/study conducted according to a standard is more readily accepted in a court of law.

Standards or guidelines have more to do with survey procedures and data quality than with interpretation or the ultimate use of the data.

Question 2: How do the results of GPR surveys fare when exposed to regulatory requirements (NAGPRA, CERCLA, RCRA, ...)? Would standards or guidelines help?

Olhoeft--Regulations are being changed as a result of what we can do with geophysics. Some new regulations will specify geophysical surveys.

Annan--We are learning that contaminant migration processes are more tightly coupled to geology than to hydrology, particularly for DNAPL's. Awareness of this fact will necessitate increased use and acceptance of GPR survey results.

Bevan--In archaeological applications of GPR, the archaeologist practitioners have standard procedures based on %-coverage. The results of GPR surveys are given to the archaeologist-in-charge to make any certifications.

Question 3: Would there be value to a "government clearinghouse" for GPR information, e.g., reputable GPR contractors and their track record, successes and failures wrt. area of application, soil/rock types, moisture conditions, etc., and government sources of technical assistance?

In the past there was an Interagency Geophysics Coordinating Group which met yearly to discuss Geophysics programs; this group published a proceedings, but is no longer functioning. Apparently, there is an informal group which meets in the Washington, D.C., area to discuss geophysics programs, but nothing formal is published. The old interagency group was perceived to play a valuable role in avoiding duplication of effort and technical interchange.

Question 4: Are you aware of any instances where GPR contractors and government users/practitioners have had "conflict" wrt. GPR execution? (i.e., conflict of interest, government versus private execution regulations, etc.)

The general consensus was that in most cases there are no problems. Government practitioners will generally conduct GPR work in-house only (a) when the work involves unusual aspects, (b) strictly research objectives, or (c) involves emergency factors or time constraints which preclude contracting. Most government practitioners freely recommend and/or utilize GPR contractors in other situations.

Question 5: What is the potential of airborne GPR for hazardous waste site characterization and subsurface mine (the explosive kind) and unexploded ordnance detection and mapping?

In general airborne GPR has potential for all these applications; however, there are "charlatans" overselling the potential and presenting untenable results. There is little change for success with airborne GPR in urban areas. Airborne is currently being evaluated for mine and unexploded ordnance detection, but the results are classified.

Question 6: What is the single most needed area of research and development in GPR?

As is often the case with questions like this, the panel members had trouble limiting their response to a "single" area.

Fenner--data reduction and imaging

Doolittle--more affordable systems

Annan--better knowledge of antenna patterns and then making use of that knowledge
--procedures for determining near-surface geoelectric properties and then correcting the GPR data for changes making use of the antenna pattern
--techniques for visualization of massive amounts of GPR data

Olhoeft--the greatest need is education, including better awareness of capabilities and especially GPR limitations; GPR needs to be introduced in university curricula
--better antenna design
--automated data processing

Question 7: Is it desirable to continue Government Users Workshops on GPR on an annual basis, perhaps rotating among the relevant agencies (USGS, EPA, DOE, DA, COE, etc.)?

There was not much comment in response to this question among the panel members, however an EPA representative in attendance felt the workshops should continue and volunteered to host the next one.

END