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NEARFIELD ELECTROMAGNETIC DETECTION OF MINES

FINAL REPORT

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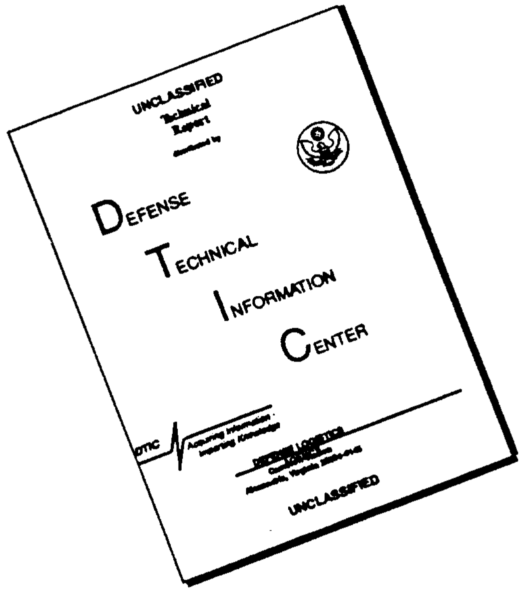

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Experimental and analytical research on mine detection is described. The objectives were the design of measurement system for evaluating mine detection ideas and a plan for investigation. The approach was electromagnetic waves for ranges less than 3 meters. The report has three parts. Part I presents analytical and experimental data, describes equipment and reviews identification; it is the basis for design of a measurement system and the technical plan. Part II describes system design; Part III the technical plan.

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OVERVIEW

Introduction

The report describes a project of research on electromagnetic wave methods for detecting and identifying diverse land mines in diverse environments.

The project had two objectives. One was to design a measurement system for testing new mine detection ideas. The second was a technical plan for measurements with the system and subsequent analyses of the data.

Land mines are a venerable but continuing threat. Although technological countermine methods have been developed to reduce the need for probing by soldiers, new kinds of mines and emplacement methods defeat current countermeasures. For example, electromagnetic detectors can locate metallic mines but fail to detect dielectric mines in dry soil. Other countermeasures include unearthing or exploding mines but these approaches have problems so interest persists in detection.

Several detection methods have beeb developed. Nuclear, magnetic, and chemical methods have potential but suffer from debris and chemical residues in battelfields. Electromagnetic methods have success in detecting metallic methods but are less capable of detecting dielectric mines.

The utilization of electromagnetics in a practical, fielded system also requires the ability to discriminate between mines and other objects; otherwise time is lost in exploring undesired objects such as roots.

The approach to the system design and the technical plan contained several phases which were selected logically on the basis of experience in locating mines and buried dielectric anomalies. Initially measurements were done and interpreted to determine critical components and experimental conditions. Available measurement components and practical procedures were than reviewed. Simultaneously, methods were evaluated for data acquisition and mine identification. Finally, emerging technologies were considered. The results were a rational basis for sytem design and evolution and for the technical plan.

The following assumptions bounded the scope of the work.

- Electromagnetic waves would be used because of their demonstrated potential and because other projects are studying alternatives.

- Radiating and receiving antennas are outside the soil. An antenna in or on the soil may couple energy efficiently but is immobile. Antenna height is less than 3 meters because other projects are investigating farfield methods.

- Wave frequencies in the 0.3 to 2 GHz range were emphasized to compromise attenuation, clutter, and resolution. The higher frequencies may be useful for imaging.

- Commercially available equipment was considered for the measurement system design to obtain accuracy and generality without developing new equipment. Emerging technologies were also included to provide a basis for evolution of the system.

By interpreting experimental results we selected and evaluated key parameters for detection and thus for measurement system design. Emphasis was on the structure of the field near a mine. The data guided the selection of equipment, such as antennas and receivers, for the system. The data also helped define the technical plan by identifying parameters needing study. The measured data were processed to evaluate acquisition methods and detection algorithms to select analytical methods for inclusion in the technical plan.

Emerging techniques were evaluated. Parallel processing accelerates digital computation for identification and suggests parallel data acquisition by antenna arrays. New receiver configurations were devised. Holographic imaging merits study because the rough soil surfaces are diffusers, which improve holographic images. This filtering occurs by diffraction from the hologram, without a filter, and can be done in real time. Neural networks may be useful in filtering measured data as a preliminary to identification methods; the extent of necessary measurements needs evaluation.

RESULTS: SYSTEM DESIGN; TEST PLAN; GROWTH

Extensive data were measured in both monostatic and bistatic arrangements were used to determine the structure of fields near mines. Frequencies ranged from 0.3 to 1.1 GHz. Several antenna types were evaluated including dipoles, three-dipole arrays with null and maximum type patterns, and stacks of dipoles. Polarization had relatively little effect in our test cases.

We discovered some new results. Antenna height significantly influences reflectance. We developed an apparently new idea, a universal curve for reflectance as a function of height to wavelength ratio; this curve unifies data for a band of frequencies.

We investigated periodically grooved surfaces and found that the intensity has oscillations that are periodic with the same period as the grooves. The intensity oscillations decrease as antenna height is increased.

Clearly, antenna height is a significant parameter.

Processing improves detection and identification. Edge enhancement was demonstrated by Sobel processing, which differentiates measured data. Another differencing method combined with autocorrelation showed promise. Holographic images are shown for a buried square anomaly; images were improved by subtracting a background field value measured while an antenna scanned an area.

Two system designs are presented. One operates in the band 0.3 MHz to 3 GHz; the other in the band 0.045 to 20 GHz. The lower frequencies system is less expensive. Cost estimates are included. Methods for scanning antennas are described. The design assumes present day equipment.

A detailed technical plan is presented. Tables describe combinations of variables such as antennas, frequencies, antenna heights, polarization, etc.

Methods for increasing capability are suggested. Parallel data acquisition seems a feasible way to accelerate data acquisition. Parallel processors can accelerate digital computation. Imaging is suggested as a means for simplifying pattern recognition. Neural networks may become useful as a way to prefilter data for recognition; this possibility requires critical review because necessary data sets may be large. Optical computing may become useful. New network analyzers may be developed to accelerate data acquisition.

INTRODUCTION AND SUMMARY

Motivation

Land mines threaten Army operations by causing casualties and reducing mobility. The threat is serious because countermeasures are inadequate for many current mines; moreover, new mines and emplacement methods are being developed.

Several countermeasures exist, but all have deficiencies. One countermeasure is to explode mines by rollers, explosives, or electromagnetic waves; the special equipment and personnel complicate logistics and explosions in roadways require repairs. Another countermeasure is to plow a mine field with an armored vehicle and to dispose of unearthed mines; searches without information on location are slow. A third countermeasure, probing by soldiers, is very slow and dangerous. A fourth approach is detection by electronic equipment and subsequent marking and removal.

Detection is desireable for several reasons. First, detected mines can be avoided and removed. Second, a detector may be operationally simpler than a plow or roller; of course, the detector must be mobile. Third, resources such as tanks, plows, or other detonating methods may be too expensive.

Detection, however, is difficult. The mine threat is diverse. Mines can be metallic or almost entirely non-metallic. Detectors for metallic mines exist, but the Army lacks a detector for dielectric mines. In addition, detectors must operate in diverse, adverse, and hostile environments.

The need for detecting dielectric mines motivated the research described in this report. Electromagnetic methods for detecting dielectric mines probably will detect metal mines.

Objective

The research had two objectives. One was a design for a measurement system to serve as test bed for mine detection. The second was a technical plan for analyses and experiments with the measurement system to evaluate new approaches and hardware systems for mine detectors. These objectives are two steps in solving the problem of detecting diverse kinds of mines in diverse environments. A measurement system will help to evaluate a large body of existing measurement and processing techniques, and it will help to initiate new ideas.

Approach

The approach was an analytical and experimental investigation that assumed the use of electromagnetic waves. Prior research and development have demonstrated the potential of electromagnetic waves for mine detection.

The approach has difficulties because the differences between the dielectric constants of soil and those of dielectric mines are often small. Another difficulty is that mines have diverse sizes, ranging from a few inches to approximately a foot across. In addition, the air-soil interface reflects, masking the object-scattered field. Moreover, soil properties vary.

The electromagnetic wave approach was restricted to nearfield scattering; that is, for distances less than approximately three meters from a mine.*

We sought to understand and describe how mines and soil surfaces diffract electromagnetic waves. Diffraction is significant because the wavelengths used are in the range of tens of centimeters. These wavelengths reduce attenuation by the soil and reduce clutter from scattering by roots, rocks, and surface roughness.

We sought also to evaluate data processing methods that detect and identify mines and discriminate against rocks, roots, and other objects. Methods included the following: spatial differentiation of measured phase and intensity, finite differencing followed by autocorrelation, and holographic imaging. Imaging seems

* Other studies are considering techniques for greater distances.

useful for pattern recognition because focused image shapes and sizes are, to a good approximation, independent of object depth and antenna height. An image of an unknown object can be correlated with a data base of images of known mines. It is significant that a data base of images would be smaller than a data base of measured reflectance data.

Alternate approaches utilize acoustic, magnetic and nuclear methods. Because these methods are being studied in other Army-sponsored projects, they were not included in this research project.

The results of the investigation are a basis for measurement system design and for the technical plan.

Structure of the Report

This report consists of three parts, as follows.

- Part I presents analytical and experimental results that are the basis for the design of the measurement system and for analytical and experimental investigations. This part consists of eight sections; each describes a subsystem of the measurement system or a key aspect of mine detection.
- Part II describes the design of the measurement system. It describes a design that operates at frequencies up to 3 GHz. It also describes an alternate design for operation at frequencies up to 20 GHz.
- Part III presents a technical plan for analytical and experimental investigation of mine detection ideas with the measurement system.

Overview of Part I

Part I represents analytical and experimental results that are the basis for the design of the measurement system and for a technical plan of analytical and experimental investigations with the system. Part I consists of eight sections. Each section describes a key aspect of the measurement system's design. In doing so, the sections also discuss mine detection and identification. Some of the sections discuss apparatus; performance and cost trade-offs are presented. Other sections discuss mines and the environment. Still other sections discuss physical processes and measurement procedures. Finally, processing is discussed. The eight sections of Part I are listed in Table S-1 and pictured in Figure S-1.

TABLE S-1

ASPECTS OF A MEASUREMENT SYSTEM FOR EVALUATING MINE DETECTION IDEAS

1. *Radiation* - A source generates radiation in the form of microwaves.

2. *Radiation Launching* - The microwave energy propagates from the source by means of transmission lines to antennas, which radiate, or lauch the energy toward the soil.

3. *Environment* - The environment is the material surrounding a buried object. Surroundings include the soil, roots, foilage, and debris. The environment varies with position and time to complicate detection.

4. *Mines* - Many kinds exist. Some are metallic; others, dielectric. Some are large; others, small.

5. *Scattering* - Waves are scattered by a mine; in addition, the air-soil interface, rocks, and roots also scatter to complicate detection.

6. *Radiation Reception* - Scattered fields are received by antennas.

7. *Detection; Receiving Equipment* - Detection requires a receiver, which may measure phase, intensity, or both.

8. *Processor* - A processor digitizes and stores data. It controls portions of the system. In addition, it may evaluate detection and identifiction algorithms.

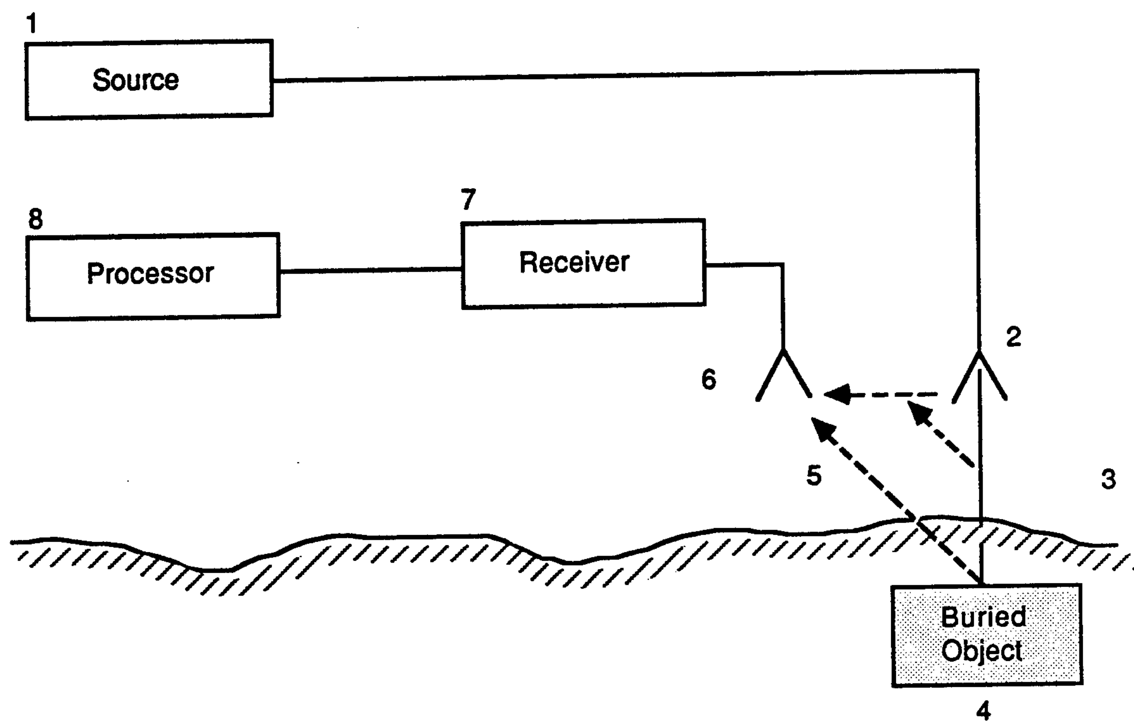

Figure S-1. Overall Organization of a Measurement System. The Numbers in the Figure Refer to the Categories in Table S-1.

Summary of Part I

The eight sections of Part I are summarized in the following paragraphs.

1. *Radiation* - Sources of radiation are reviewed. Two commercially available sources are recommended; these sources produce continuous waves. One has a higher maximum frequency than the other. Although pulsed sources are potentially useful for detection, pulsed radiation is more special than continuous waves, which can be used to test diverse aspects such as antennas, clutter, and scattering. Moreover, pulses can be synthesized from a set of continuous waves at discrete frequencies.

2. *Radiation Launching* - Several types of antennas are described. Properties such as frequency bandwidth, radiation patterns, and polarization are compared. The measurement system should have several antennas available. It should also provide means for supporting one or several antennas and means for adjusting antenna height and orientation.

3. *Environment* - The influence of the environment is described. The air-soil interface reflects, producing clutter that masks the field scattered by a mine. Rocks and roots scatter, further complicating the observed fields. The magnitudes of the scattered fields depend on differences between refraction indices at discontinuities. Surface roughness causes more or less random scattering; diffuse scattering might be exploited by holographic processing. Shallow water presents a problem.

4. *Mines* - Scattering by mines depends on the difference between dielectric constants of the mine and the soil. A simple formula is described. Reference is made to data which suggest voids in dielectric mines are a source of scattered fields that lead to detection.

5. *Scattering* - Wave scattering is the physical mechanism that involves a buried object and leads to information about it. Unfortunately, the air-soil interface also scatters; the scattered field masks the object scattered field. In addition buried roots or rocks and surface height changes scatter; these fields produce signals that can be mistaken for desired objects.

Theoretical descriptions of scattering are reviewed. Theories range from simple ray pictures to integral equation methods. A simple formula relates scattered amplitude to the volume and dielectric constant of the buried object.

Antennas influence scattering. Antenna proximity to the soil and object is a factor, as is antenna orientation. These variables influence the polarization of the incident wave and thus scattering; they also influence the size of the region that scatters. In addition both guided and unguided waves can be excited.

Scattering from rough surface is discussed. Experimental results are given for corrugated surfaces. Corrugations improved microwave holographic images. The reflectance measured by scanning an antenna over an object under corrugated soil varied spatially with period identical to that of the corrugations. It is significant that the periodic reflectance variations were smoothed out by increasing the height of the measuring antenna.

The influence of object depth on scattering was established as a significant parameter. Measurements were made for a metal plate buried at several depths. The spatial distribution of the varied field varied significantly, and the peak value of reflectance decreased logarithmically with depth, to a good approximation. This result is significant for automatic detection by correlation; measured data depend on depth so imaging may be justified to get an object representation that is independent of depth.

6. *Radiation Reception* - Radiation is received by antennas and transmission lines. Measurements can be made with a monostatic arrangement, in which one antenna both transmits and receives, or with a bistatic arrangement, in which one antenna transmits and another receives. Several kinds of antennas are described. Key parameters, such as frequency bandwidth for effective operation and radiation patterns, are compared.

Antenna arrays consisting of three elementary antennas produce a pattern with a broadside minimum for transmission but a maximum for reception; these antennas can reveal edges of buried objects, but they give nuisance alarms at abrupt surface height changes. Nuisance alarms motivate identification by imaging.

Methods are described for scanning an antenna over an area near a buried object. Scanning can provide a comparison of regions which scatter differently and thus possibly reveal a mine.

Height dependence of the scattered field is discussed. Experimental results show reflectance, measured with a monostatic, dipole antenna, has a maximum for very small heights, a minimum at somewhat larger heights, and another maximum at even larger heights followed by a gradual decrease. If reflectance is plotted as a function of height to wavelength ratio, curves for a wide band of frequencies follow a common locus to a good approximation. This curve illustrates the complexity of nearfield scattering by an object and the complexity of nearfield measurement. The measurement system should have a means of changing antenna height as well as means for changing antenna orientation.

The nearfield distributions of antennas can be measured with the same electronic equipment that measures the fields scattered by buried objects. Of course, antenna translation mechanisms must be suitable.

7. *Detection; Receiving Equipment* - A receiver detects the scattered field which is picked up by an antenna. Key receiver performance parameters are defined. Several receivers are described and compared on the basis of performance and cost. All receivers measure phase as well as intensity.

Recommendations are made on the configuration of a source and receiver. One recommended system operates in the frequency band from 0.3 MHz to 3.0 GHz. An alternative system would operate over a wider frequency band, 0.045 to 20 GHz. Frequencies above 3 GHz may be of interest for testing radar, imaging concepts, scattering, or soil propagation; however, cost is greater than for the lower frequency system. Cost estimates are given in Part II.

A new digital, sampling oscilloscope is an optional item. It may be useful for evaluating broadband, short pulse detection ideas.

8. *Processor* - The processor performs two functions. One is in data acquisition by controlling parameters such as frequency and by digitizing, storing, and displaying measured data. The other is to process the data by calculating gradients or correlations, by forming images, or by analyzing resonances.

Data acquisition involves several considerations. The number of channels must be adequate to transmit data on phase and intensity of the measured field, on frequency, and on antenna position. Sampling is essential; data must be adequately sampled to avoid problems such as aliasing, and mechanisms must be provided for triggering samples of scattered field data and position.

A computer was selected. Current scientific personal computers can digitize and store measured data, and they can calculate transforms and correlations. Software must be set up for sampling, storing, and displaying data; in addition, software should control scanning and frequency.

Several detection and identification methods are discussed. These include direct interpretation of measured data by studying variations or computing gradients. Sobel edge enhancement, a gradient technique, is described. A new method, based on phase switched interferometry combines gradients and auto-correlation. Holographic imaging by backward propagation is another method that has yielded good images for both smooth and corrugated soil. Imaging is recommended because it discriminates against rocks and roots. In addition, images, formed from measured data, have the same size as an object; therefore, correlation, or pattern recognition, with images of known objects is simpler than comparing the measured data directly with a base of measured data that depend on depth and antenna height. Additional methods such as spectral filtering, deconvolution, and pattern recognition are discussed.

Summary of Part II

Section 9 describes two alternate designs for the measurement system. One system operates in the frequency band 0.3 MHzto 3 GHz; the other from 0.045 to 20 GHz. Detailed lists of subsystems such as a network analyzer, computer, and positioners are given. Candidate antennas are described. An optional sampling oscilloscope is described. The two systems differ in estimated cost. The catalog cost of the lower frequency system is $55,000. The cost of the higher frequency system is $123,000.

Mobility of the system is described. Detection requires scanning an antenna over an area. Positioners are suggested for polar and rectangular scans. A cart or vehicle for moving the system is recommended as a way to scan large areas, especially for outdoor field tests.

Additional options for the system are described. These are mainly suggestions on processors. Although a conventional scientific personal computer is recommended for the measurement sytem, new, parallel processors are reviewed. Parallel processing may be necessary in new mine detectors to identify or recognize diverse mines in diverse and adverse environments. Identification may require large amounts of data from distributed sensors and mutliple frequencies. New configurations of mines may require applying processing concepts such as neural networks and adaptive methods; these methods require fast processors. Optical parallel processing is a possibility for real time imaging.

Summary of Part III

Section 10 describes a technical plan for analytical and experimental investigations with the measurement system.

Extensive measurements are planned in a laboratory setting, of mine lanes, to obtain controlled conditions. The main goal is to determine the spatial distributions of phase and intensity for diverse mines; the effects of antennas, antenna position, mine depth, and frequency would be evaluatled. Arrays of antennas for parallel data acquisition will be tested. Measurements will be made for both rough and smooth soil.

A substantial number of outdoor measurements is planned to evaluate the effects of soil roughness on diffusing the reflectance.

Measured data will be compared with scattering theories.

The data will be processed with a number of algorithms. Holographic imaging is of interest for identification; exisiting programs will be modified for the system's computer. Gradient techniques, such as the Sobel algorithm, will be applied. Spatial Fourier transforms will be calculated, and filters will be designed.

Adaptive and neural network methods will be analyzed for their potential applicability to mine detection.

PART I

EXPERIMENTAL AND ANALYTICAL BASIS FOR MEASUREMENT SYSTEM DESIGN

This part of the report presents experimental and analytical results that are the basis of the design of the measurement system, which is described in Part II.

1.0 RADIATION: SOURCES

1.1 General Aspects

For this report, radiation is radio frequency energy that propagates as electromagnetic waves. Radiation has many properties; these include wave frequency, bandwidth, polarization, modulation, and coherence. These properties are determined mainly by the instrument that generates the waves. We call this instrument the source. Wave polarization is discussed in the following section, Wave Launching, because polarization depends on antenna structure. Here, in Section 1.0, the emphasis is on sources.

We distinguish between sources that generate short pulses of energy and those that generate very nearly sinusoidal waves over relatively long intervals. We call the former impulsive sources; the latter, continuous wave* .

1.2 Continuous Wave Sources

Two kinds of continuous wave sources exist. One kind is a sweep oscillator; the other, a synthesized source. Briefly they are described as follows.

• *Sweep Oscillators.* Typically these sources have a voltage-controlled, solid state oscillator, such as a Gunn diode. Frequency is changed, or swept, over a

* The effects of pulses can be realized from monochromatic waves by Fourier synthesis over a frequency band. New network analyzers perform this function; see Section 7.

band; fixed frequency signals also can be obtained.

• *Synthesized Sources*. These sources usually have a crystal controlled oscillator and use frequency multiplication. They are tuneable and provide a choice between a fixed frequency or a band.

Fourteen commercially available sources are listed in Table I which also includes some key performance parameters. In general, sweep oscillators cost less than synthesized sources, but they have higher spurious oscillations and lower frequency accuracy.

1.2.1 Frequency Accuracy

Frequency accuracy is significant. The reason is that frequency diversity may improve mine detection by choice of frequency to reduce clutter, enhance mine scattering, or separate clutter and mine returns.

Frequency accuracy is necessary because errors obscure interpretations of frequency dependence of scattering. In addition, components such as antennas have frequency dependent properties. At the theoretical level, frequency errors would cause discrepancies between measurement and calculation of scattering from the soil and a buried object.

Frequency errors also can complicate measuring the phase of reflected fields. Suppose a phase sensitive receiver, such as a network analyzer is used.* These receivers compare signals that propagate over two paths, which consist of air, soil, the object, and transmission lines such as co-axial cables. One signal path, is from the source to the antenna and soil. The other, reference path, is a fixed transmission line. If the path lenths are unequal, frequency errors cause phase errors.

To estimate magnitudes consider a path length difference L. The phase difference is

$$\Delta \varnothing = 2\pi L/\lambda = 2\pi Lf/c \tag{1-1}$$

* This supposition is justified in Section 7.

where λ is wavelength, f is frequency, and c is phase velocity. For differentials δf and δL in f and L respectively, the differential in $\Delta \phi$ is

$$\delta(\Delta \phi) = 2\pi \, [(\delta L/\lambda) + (\delta f / f)(L/\lambda)] \qquad (1\text{-}2)$$

The factor L/λ multiplies the phase error caused by a fractional frequency fluctuation ($\delta f / f$). For example a path length difference of one wavelength at 1 GHz, or 11.8 inches, causes an error of ±1.8° for frequency errors ±5 Mhz, which is the accuracy for a sweep oscillator in Table 1-1.

Both path lengths can be approximately equalized by selecting cable lengths in the two paths. Phase can than be adjusted modulo 2π by the receiver; however, when frequency is changed, adjustments are required. In principle, equalizing path lengths seems simple, but in practice difficulties exist. First, the wave propagates in soil. Second, environmental heating may change the two paths differently.

The consequences of ±5 Mhz phase error suggest selecting a synthesized source rather than a swept oscillator. A synthesized source and network analyzer can be an integrated unit A swept oscillator with a counter would give acceptable frequency accuracy but the counter would be an extra unit, adding cost, requiring adjustments, and cabling. A synthesized source is simpler.

1.2.2 Maximum Frequency

The choice of a source for the system depends on the maximum frequency that the source can produce.* As shown in Table 1-1 maximum frequencies range from 2 GHz up to 26.5 GHz. Figure 1-1 summarizes frequency range, along with frequency error..

The maximum frequency for the measurement system justifies a brief historical review. Frequencies in the range 300 to 600 Mhz were used in the AN/PRS-8 man portable detector; the idea was to reduce clutter by subtracting a

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* Lower bounds on frequency are less critical than upper. All but three sources in Table 1-1 operate down to 100 MHz. Frequencies below about 100 MHz seem impractical because they would require large antennas and give low resolution.

TABLE 1-1
SOURCES

SOURCE	FREQUENCY BAND (GHZ)	FREQUENCY ACCURACY (MHZ)	POWER OUTPUT (DBM)	SPURIOUS SIGNALS (dBC)	CATALOG COST ($$10^3$)	REMARKS
SWEEP OSCILLATORS:						
1. HP* 8350,83522A	0.01-2.4	±5	13	-30	13	YIG oscillator; GaAs amplifier
2. Source 1 & 5342A counter	0.01-2.4	±0.1	13	-30	20	above + counter
3. HP 8350,83592	0.01-20	±5	10	-35	28	YIG
SYNTHESIZED SOURCE						
4. SA+ 21508	0.1-2	±15	7-12	-15	15	2 plug-in units
5. SA 21508	0.1-18	±15	7-12	-15	37	4 plug-in units
SYNTHESIZED SIGNAL GENERATORS:						
6. HP 8663	.01 - 2.56	10^{-6} at 2 MHz	16	-78 to -90	46	crystal oscillator, phase locked
7. HP 8673	2 - 26.5	10^{-6} at 2 MHz 2×10^{-5} at 20 MHz	8	-58 to -70	45	crystal oscillator, phase locked
8. HP 8753 (inc: receiver)	0.0003 - 3	10^{-3}	13	-32 to -50	35	included in network analyzer
9. SA 2150 and 2185	0.1 - 2	2×10^{-3}	13		29	
10. SA 2150 and 2185	0.1 - 4	4×10^{-3}	13		33	3 plug in units
11. SA 2150 and 2185	0.1 - 18	1.8×10^{-2}	13		56	5 plug in units
12. Wiltron 360MS18 (inc: receiver)	0.5 - 18				100	included in network analyzer
SYNTHESIZED SWEEPERS						
13. HP 8341B	.01 to 20	10^{-6} at 1 GHz	9 to 12	below -50	40	
14. HP 8340B	.01 to 26.5	2×10^{-5} at 20 GHz	1 to 12	below -50	55	

* HP stands for Hewlett-Packard
\+ SA stands for Scientific Atlanta

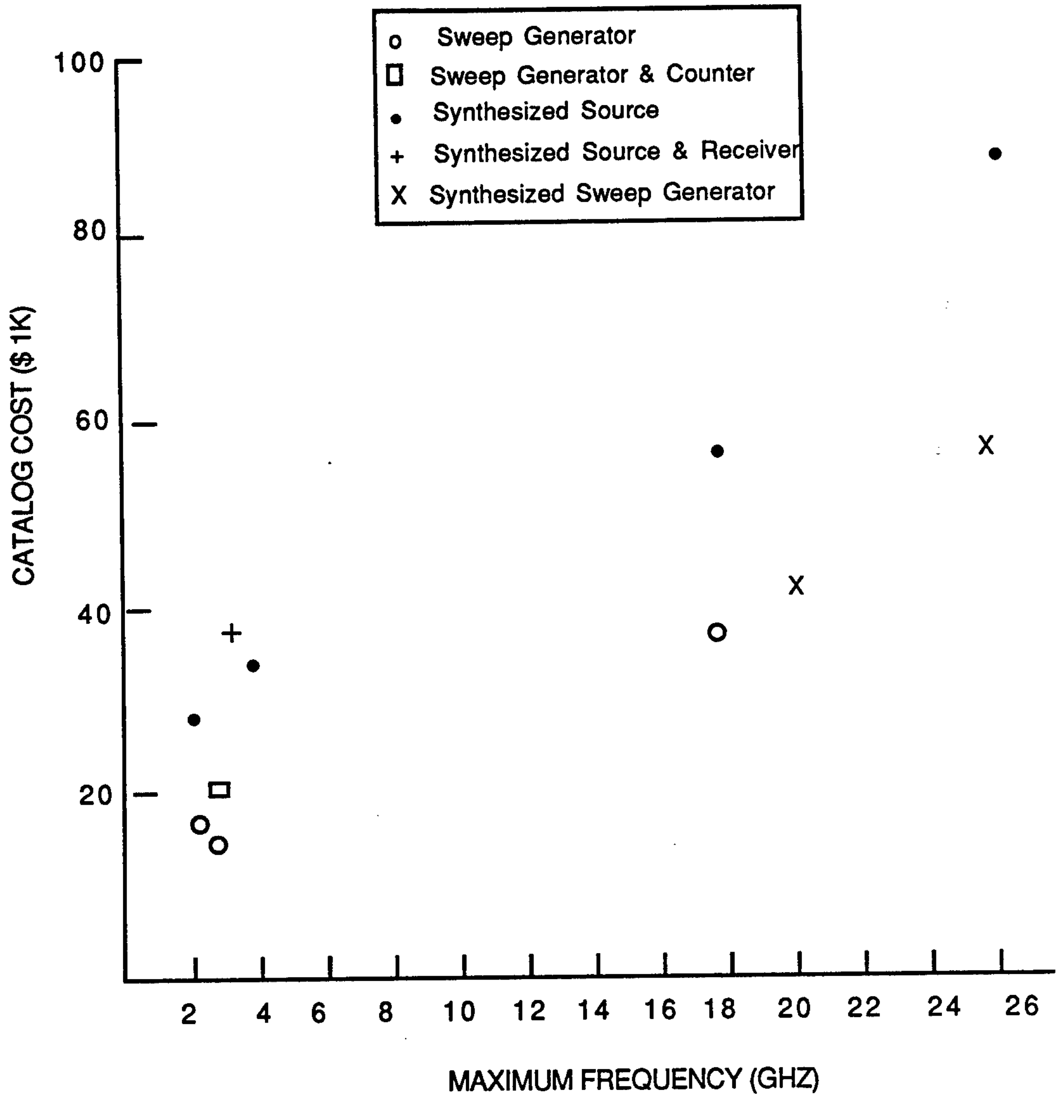

Figure 1-1. Maximum Frequency and Catalog Cost of Sources. Note that + is for Source and Receiver.

background signal with averaging over frequency** [1]. Frequencies near 1 GHz were utilized in experiments on a separated aperture system that involved guided wave propagation.[2] Microwave holographic images of mines were made with 2.3 GHz waves in laboratory experiments.[3] A frequency modulation radar operated in the band 2 - 4 GHz.[4]

The maximum frequency selected for the measurement system will be a compromise between attenuation and resolution in potential mine detector systems. Attenuation depends on soil conditions and mine depth so an adequate frequency range is not obvious.

1.2.3 Cost

Maximum frequency is related to cost, as shown in Figure 1-1. Costs of synthesized sources are under $37,000 for maximum frequency 4 GHz, but costs increase to $58,000 for 18 GHz and to $91,000 for 26.5 GHz.*

The Hewlett-Packard 8753 Network Analyzer contains a synthesized source and a phase detector. This instrument is accurate and convenient; however, it's maximum frequency is 3 GHz. This maximum is reasonable, but higher frequencies may be useful.

1.2.4 Recommendations

Two alternative configurations are suggested.

If operation up to 3 GHz is adequate, the Hewlett-Packard 8753 Network Analyzer is recommended; the source is included.

If higher frequencies are desired, for diagnostics, imaging, or radar, the Hewlett-Pakard 8341B is recommended. The frequency coverage is .01 to 20 GHz. A receiver would be necessary for this source. Receivers are described in Section 7.

** References are indicated by a numerical superscript. They are collected in Section 9.

* These costs are for sources bought separately from receivers. Savings can be realized by purchasing sources and receivers as a system. This possibility is discussed in Section 7.

Hewlett-Packard sources are recommended because they are accurate, stable, cover wide frequency ranges, and are cost competitive. In addition, they are compatible with accurate receivers and convenient computers to form an integrated system.

2.0 RADIATION LAUNCHING: ANTENNAS

2.1 General

Radiation launching means transferring the radio frequency energy from the source toward the soil through transmission lines and antennas.

The transmission lines will be either co-axial cables or rigid metal waveguides. For frequencies up to approximately 8 GHz, co-axial cables are appropriate because they are compact and cause little attenuation. For frequencies above approxmately 8 GHz, rigid waveguide is compact and has little loss. With either kind of transmission line, components such as connectors and power dividers must be well matched to reduce reflections, which can cause errors. The transmission lines should be short to avoid phase changes that result from temperature changes; therefore, the source and receiver should be close to the antennas.

The test system will have an antenna to radiate energy. The antenna's configuration probably will depend on the idea that is being evaluated. Although the system may be used to evaluate new antenna concepts and antenna nearfield properties, some conventional antennas should be included for measuring data that will be analyzed to evaluate scattering theories, soil properties, or processing methods.

The orientation and height of the antenna will influence measurements of scattered fields. Orientation influences incidence angle and polarization relative to the soil; these variables influence scattering. Antenna height influences the size of the illuminated region and wavefront shape.

As a preliminary, let us introduce some terminology. A single antenna may both radiate and receive; this arrangement is called monostatic. Alternately, one antenna may radiate, and another may receive; this arrangement is called bistatic. More general arrangements, consisting of arrays of individual antennas may be useful.

2.2 Specific Antennas

The rest of this section describes specific antenna configurations which can be used to lauch radiation. These antennas can also be used for reception, which is discussed in Section 6; that section also describes bistatic operation and arrays of antennas. Antennas suitable for radiation are as follows.

Linear Dipole. This antenna consists of two colinear wire segments connected to a transmission line such as a co-axial cable. The wire segments have overall length approximately a half wavelength.

These antennas have narrow impedance bandwidths.* Standing wave ratio is less than 2 for approximately 10% of the center frequency. Outside this band, large reflections occur so a system would be inefficient and inaccurate when used for reception, significant energy is scattered rather than absorbed.

Dipole antennas requires baluns or matching transformers; both must be precisely made to avoid reflections.

Loaded Dipole. A dipole's bandwidth can be broadened by gradually increasing the diameters of the wires towards the ends, away from the central region connected to the transmission line. Flat, loaded dipoles resemble wedges, with points near the transmission line.

Frequency Independent Antennas. These antenna have bandwidths an order of magnitude greater than those of dipoles, but they are not truly frequency independent despite the name. One type, the Yagi-Uda array consists of several parallel rods that are orthogonal to and spaced along the transmission line. The antennas radiate from an active region that varies in position along the transmission line with frequency. Antennas of this type may be useful in the measurement system because their broadband properties can reduce the number of changes in measurement; moreover, multiple frequency data can be obtained in a single sweep over a buried object by multiplexing frequencies.

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* Wide band antennas would simplify measurements. Five dipole antennas would be needed to cover a band from approximately 300 MHz to 1100 MHz. Changing antennas takes time and requires calibrating phase and intensity.

As will be shown in Section 6, antenna height above the ground is a significant parameter so the frequency variation of the active region's position may be useful for detection. These antennas are bulkier than dipoles so they may be less convenient and cause more scattering.

Stacked Dipoles. Two or three dipoles can be arranged in a vertical stack and fed with separate transmission lines through switches. A potential advantage is simplicity of connections because of the narrow bandwidth of each channel. Another potential advantage is the possibility of gathering data at several spaced frequencies over a wide bandwidth in a single sweep over a target; the accelerated data gathering would save time in a measurement system and it is an idea for inclusion in a mine detection system. It seems necessary to study the number of frequencies that would be necessary to detect a variety of mines.

Horns. Horn antennas are hollow pyramids or sections of cones with metallic walls. These antennas have wide bandwidths, but they are bulky and require an aperture approximately a wavelength for efficient radiation. The illuminated region on the ground may be large, increasing clutter. Horns would be convenient for frequencies above about 1 GHz.

Paraboloidal Reflectors. These antennas have a reflecting surface with a feed such as a dipole or log periodic near the focus. They are rather large, a few wavelengths in diameter at least; however, they can be focused. They may be useful for higher frequencies, say those exceeding about 1 GHz.

Loops. Wire loops may be useful because their patterns have nulls in the broadside direction. Their orientation may be a problem because their polarization contains horizontal and vertical components of electric field when the plane of the loop is vertical; propagation modes in the soil differ for the two polarizations.

3.0 ENVIRONMENTS

3.1 Influence on Detection

By environment we mean first of all the material surrounding the buried object. The surroundings include the soil, roots, foilage, and possibly debris such as metal particles.* In general, the environment is not uniform; however, uniform conditions can be set up in laboratories such as mine lanes.

Another aspect of the environment is its variability. Spatial variation results from the soil's inhomogeneity, both vertically and horizontally. Roots, rocks, and debris also contribute.

Moisture is another source of variation. Moisture content depends on weather, and it may depend on depth into the soil. Moisture influences complex-valued dielectric constant and thus affects reflection and attenuation. Moisture may be beneficial if it increases dielectric constant constrast between a buried object and soil to increase object-scattering; of course, surface reflection and attenuation can increase so signal to clutter ratio needs evaluation.

Surface reflection is significant because it can mask the object scattered field. The magnitude of reflection can be estimated from reflectance calculations for smooth, homogeneous soil and for plane waves incident normally, that propogates vertically downward toward the horizontal air-soil interface. Amplitude reflectance is, from Fresnel reflectance,

$$r = (1 - \sqrt{\epsilon'}) \; / \; (1 + \sqrt{\epsilon'}) \qquad (3\text{-}1)$$

For dielectric constant value four, r is -1/3 so power reflectance is 1/9, approximately -9.5 dB. This is a significant fraction of the incident field intensity.

Reflection depends on surface roughness. Roughness diffuses reflections at the air-soil interface. The diffuseness can improve microwave holographic images by reducing the specular, coherent reflection; of course, the effects of roughness

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* Shallow water is considered in Subsection 3.3.

depend on its scale relative to wavelength and object dimensions. Section 5 gives some examples.

The measured effects of roughness also depend on the height of the receiving antenna. Data will be given in Section 5 to illustrate this point. Briefly, measurements were made by moving a probe antenna over smooth and grooved sand at two heights. These measurements were made with a buried plastic block present and then absent. The reflectance for antenna height 0.06 wavelength varied with the period of the grooves; however, for height 0.19 wavelength the reflectance for ground soil was very close to that for smooth soil at the same height.

Clearly environment influences measured data; so does antenna height.

In more general terms, the environment is variable, suggesting that sensors be adapted to it. In the case of regular grooves, antenna height can be adjusted to reduce perturbations. In more complex cases, we can image a sensor of antenna height and a mechanism to adjust height or possibly a correction by data processing. Furthermore, the problem of variable moisture might be approached by adapting frequency to improve detection. All these parameters (roughness, moisture, and height) require evaluation. The evaluation of thse factors is a goal for a measurement system.

3.2 Influence on Equipment

The environment produces conditions that can damage equipment. For example, dust can damage computer disc drives; protect filters or enclosures seem necessary for field tests. The sun can heat an exposed transmission line, changing its length and thus causing phase measurement errors.

3.3 Water

Mines may sometimes be covered by shallow water. Detection is difficult because water reflects waves incident from air, and it attenuates strongly.

Two approaches seem possible. One is relatively long wavelengths; the other is to immerse the antenna.

Long wavelengths may propagate further than shorter; skin depth and attenuation co-efficients must be evaluated however.

Antennas can be immersed in water to reduce the surface reflection. The antenna must be tapered to provide some degree of impedance matching. Examples are tapered horns or horns loaded with dielectrics. Antennas for use in water may be small and convenient because of loading. Some evidence exists for the utility of millimeter waves in imaging body tissues immersed in water; this work was done at Walter Reed Medical Center.

4.0 MINES

Mines come in a variety of shapes, sizes, and compositions. Some mines are metallic; these are relatively easy to detect because metal strongly scatters electromagnetic waves. Non-metallic mines are more difficult. For dielectric objects we have shown that the scattered field is approximately given by

$$E^S = a(\kappa_s - \kappa_o)A \qquad (4\text{-}1)$$

where κ_s and κ_o are dielectric constants of soil and mine respectively, A is object area, and a is a proportionality constant. This formula was derived from a moment method integral,[1] and it was verified in measurements with AN/PRS-8 antennas.[2] The formula shows that low dielectric constrast, $\kappa_s - \kappa_o$, and small volume produce small fields, making detection difficult.

Additional, qualitative evidence for the importance of dielectric contrast was found by holographic imaging. Voids in mines are more visible than small differences between the soil and the mine itself.[3] This result suggests using frequencies as high as 2 GHz, which was the frequency for the images in Reference 3. Of course, clutter must be considered at higher frequencies, but diffuse reflection may be useful.

5.0 SCATTERING

Electromagnetic wave scattering is the physical mechanism that may reveal a buried object. Scattering produces the fields that are detected and processed to obtain information about the object.

Unfortunately, the interface between air and soil also scatters, producing fields that are called clutter, which is sometimes defined as any unwanted field. When procesed, clutter fields produce unwanted signals, called clutter signals.*

This section describes several aspects of nearfield scattering.

5.1 Theoretical Descriptions of Scattering For Smooth Surface and Regular Objects.

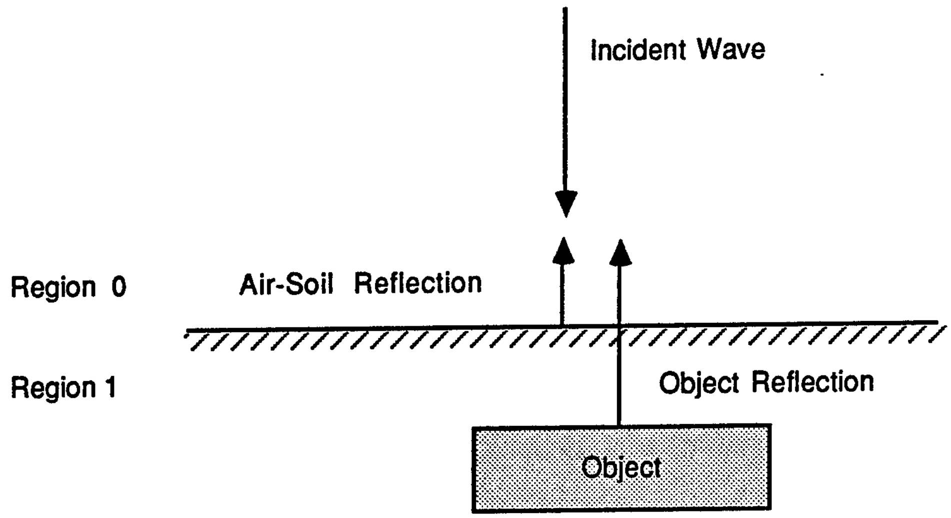
Scattering can be theoretically described in many ways, which range from simple, ray descriptions to integral equation and angular spectrum methods.

Figure 5-1(a) suggests an approximate description for an idealized case, a flat interface and a regular object. Assume a normally incident plane wave and that the wavelength in soil is somewhat less than the object's size. A ray model is reasonable for the field near the center of the object. The scattered field consists of the reflection from the air-soil interface and the object reflection; the object reflection will be described later. Reflection at the air-soil interface has magnitude.

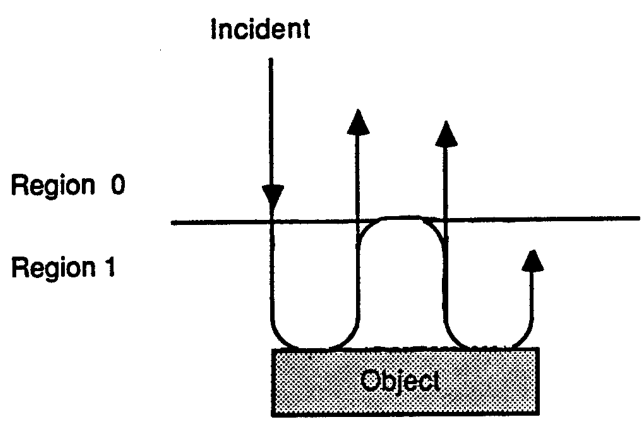
$$r_{01} = (1 - n_s)(1 + n_s)^{-1} \qquad (5\text{-}1)$$

where n_S the index of refraction of soil is $\sqrt{\kappa_S}$, where κ_S is soil dielectric constant, which for simplicity is assumed real valued by omitting attenuation. The reflected field in air is described by the reflectance R that arises from the infinite sum of rays suggested in Figure 5-1 (b). With r_{01} the Fresnel reflectance for propagation from region 0 to 1, k_1 the propagation constant in region 1, t_{01} and t_{10} Fresnel transmittances and R_{SO} the reflectance from the soil object interface.

* The distinction between clutter signals and clutter fields often is not important.



(A) Reflections From The Air-Soil Interface and From the Object



(B) Ray Model of Reflection

Figure 5-1. Reflections

$$R = r_{o1} + t_{o1} R_{so} t_{1o} e^{i2k_1 d} + t_{o1} R^2_{so} r_{1o} e^{i4k_1 d} + \ldots$$

$$= r_{o1} + t_{o1} t_{1o} R_{so} e^{i2k_1 d} (1 + r_{1o} R_{so} t_{1o} e^{i2k_1 d})^{-1} \qquad (5\text{-}2)$$

The second line follows from the first because the sum contains a geometric series after the first term. Now t_{o1} is $1 + r_{o1}$; t_{1o} is $1 + r_{1o}$; and r_{1o} is $-r_{o1}$. By substituting these relations into Equation 5-2, we obtain

$$R = (r_{o1} + R_{so} e^{i2k_1 d}) (1 - r_{o1} R_{so} e^{i2k_1 d})^{-1}. \qquad (5\text{-}3)$$

The interpretation of Equation 5-3 is that the magnitude of R depends periodically on d, the depth. For fixed thickness the second term in the numerator has period $2k_1d$; that is, the phase of the exponential is

$$\phi = 2k_1 d = 4\pi \sqrt{\kappa_1}\ d\ .$$

When ϕ increases by 2π, d increases by $1/2\sqrt{\kappa_1}$. The magnitude of R thus varies with period 2π.

Actually the description in Figure 5-1 is too simple because multiple reflections also occur within the buried object. Figure 5-2 suggests these reflections. The wave transmitted into the soil generates a reflected wave at the object-soil interface. This wave is partially transmitted, and the process continues at each interface. The reflections can be summed as before, so the reflection at the soil-object interface is

$$R_{so} = t_{o1} t_{1o} r_{12} e^{i2k_1 d} + t_{o1} t_{12} r_{23} t_{21} t_{10} e^{i2(k_1 d + k_2 t)} + \ldots$$

$$= r_{12} t_{01} t_{10} e^{i2kd} (1 - e^{i2k_2 t}) (1 - r_{12}{}^2 e^{i2k_2 t})^{-1} \qquad (5\text{-}4)$$

if we assume region 3 has properties identical to those of region 1, r_{12} is $-r_{23}$. The interpretation of Equation 5-4 is that reflectance R_{so} is zero for thickness d equal $\lambda/2\sqrt{\kappa_2}$; reflectance is a maximum for thickness $\lambda/4\sqrt{\kappa_2}$.

Clearly, frequency is an important parameter in the design of a measurement system.

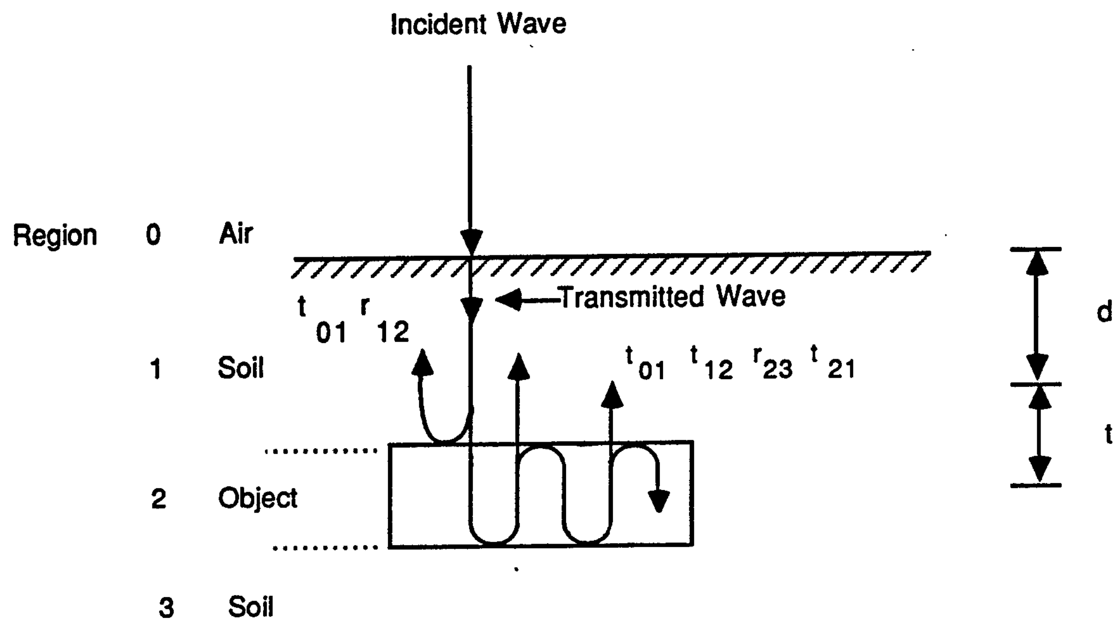


Figure 5-2. Multiple Reflections From A Buried Object

The formulas above have been generalized to account for absorbtion, but details are omitted for brevity.

The ray description is appropriate for scatterers that are large relative to the wavelength, but scattering can be described for small scatterers on the basis of the moment method. The scattered field is[5]

$$E^S = k_0{}^2 \, (\kappa_o - \kappa_s) \, (4\pi)^{-1} \int E^T \, g(\kappa_o - \kappa_s) \, dV \qquad (5\text{-}5)$$

where an obstacle in a homogeneous medium is assumed and g is r^{-1}expikr, with r the distance from source to integration point. If we assume the unknown total field E^T is the incident field and $\kappa_o - \kappa_s$ is constant,

$$E^S = \text{constant} \;\; k_o^2 \;\; E^T \, (\kappa_o - \kappa_s) \;\; \text{(volume)} \qquad (5\text{-}6)$$

If we ignore thickness variations, the area can replace the volume, and we obtain the form in Equation 4-1.

Experiments with AN/PRS-8 detectors and a variety of simulated mines verified Equation 4-1 as mentioned in Section 4.[6]

Some theories for finite objects have been developed by K. Mie [7] and D. Hill.[8] Both theories are for plane wave incidence so the effect of antenna height and hence wavefront curvature are omitted; moreover, radiation patterns of antennas are omitted. Mei's theory is restricted to bodies of revolution. Hill is extending his theory to describe antennas near the soil. We have experimentally verified some of Mei's results, but the data sample is small.

5.2 The Influence of Antennas on Scattering Measurements

The proximity of receiving and transmitting antennas is a significant factor. Wavefront curvature and scattering by the receiving or transmitting antennas were mentioned above.

Additional effects occur because the antenna orientation influences incidence angle and wave polarization. Reflectance at an interface depends strongly on incidence angle for either polarization. For parallel polarization, reflection at a planar interface vanishes at the Brewster angle.

Antenna proximity to the soil also influences the size of the region that is illuminated with appreciable signal; therefore, antennas influence the size of the region that reflects, the clutter patch.

Antenna orientation and proximity influence the types of wave modes that are excited. If the antenna is sufficiently high, approximately plane waves are incident. If the antenna is within say its diameter of the soil, surface waves can be excited, especially for polarization vertical relative to the soil surface.

The measurement system must provide flexibility for adjusting antenna position and orientation. The number of antennas is a factor in designing antenna supports. Because many kinds of antennas can be imagined, the design will be somewhat general, but special adapters may be necessary in some cases

5.3 Scattering From Rough Surfaces: Measurements for Periodic Corrugations

The roughness of the soil surface influences scattering from the air-soil interface and the total field measured when an object is buried beneath a rough surface. The magnitude, phase, and spatial distribution of the measured field depend on several variables which include the scale of roughness, wavelength of the radiation, and the size, composition of a buried object as well as the heights of the antennas. The consequences for a system depend on antenna configuration and location.

This section gives data on roughness. In particular it describes measurements of reflected fields for periodically grooved soil surfaces with and without a buried object present. The paragraph also gives data on how antenna height influences observed fields.

For perspective, let us distinguish the kinds of roughness. One is random, like that in natural terrain. Another is periodically grooved surfaces; which we produced for laboratory tests; these surfaces are regular, reproducible, and suitable for analysis. Finally, step changes in height have been used in mine lane tests with conventional hand held detectors; these steps cause detections but we do not consider them.

Distributed roughness has improved holographic images computed from measured data by an angular spectrum algorithm. Details are in Reference 3. Measurements were made with apparatus sketched in Figure 5-3. Frequency was 2.3 GHz. The antenna was a dipole in a corner reflector. It was scanned over a set of parallel straight line segments by a translation mechanism.Phase and intensity were measured for smooth soil and periodically grooved soil; as suggested in Figure 5-4. Groove period L was one inch and the vertical dimension v was 1/2 inch; the period was thus approximately 0.2 wavelength. Figures 5-5 and 5-6 show hologram data and images of a buried foam plastic block for both surface configurations. The image is more distinct for the grooved surface. Even the hologram intensity measured for the grooved surface shows the outline of the object more clearly than does the measured intensity for the smooth surface. Microwave holographic images also were improved by recording, storing, and subtracting the background level from the hologram data. The background is the field measured in the region away from the buried object. Compare Figures 5-7 and 5-5; also compare Figures 5-8 and 5-6.

Many surface profiles are possible. We studied periodic grooves because they provide a more systematic situation than do random grooves. Of course, random orientations are more natural. In work with AN/PRS-8 detectors, we found a step change in height gave a nuisance alarm in earphones; this result is an argument for a procesing method that senses gradients because a buried object's return would show a gradient on each of its sides.

The measured effects of surface reflections depend on the height of the receiving antenna. An example illustrates this point. Reflectance was measured with the monostatic system of Figure 5-9. For scans over an arc, the cart was stationary and the turntable scanned the antenna over an arc. Incidence was nearly vertical. The antenna was a dipole with a flat reflector. Reflected field phase and intensity were measured by moving the antenna over an arc at a set of fixed heights above the soil surface. Wave frequency was 700 Mhz so wavelength was 16.9 inches.

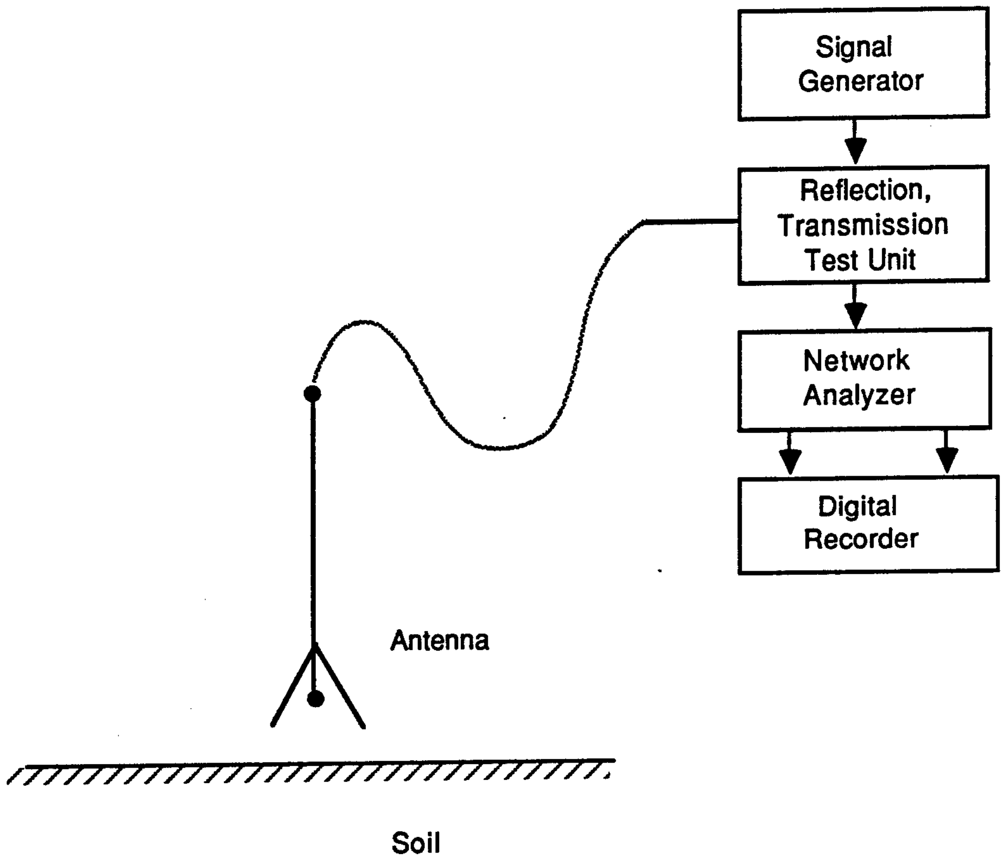


Figure 5-3. Apparatus For Hologram Formation

Measurements were made for the following conditions, with symbols defined in Figure 5-4.

- smooth soil
- corrugated soil; L: 3" ; v: 1"* 5
- smooth soil with 12" Teflon block, 2" below surface
- corrugated soil; L: 3"; v: 1"; Teflon block 2" below mean surface. 1.5

Figures 5-10 and 5-11 show reflectance for smooth and corrugated soil with the block present and for height 0.06 wavelength.**. For the corrugated soil, the reflectance is periodic, and the period very closely approxmates that of the corrugation. In Figure 5-11 the periodic variations occur in three regions because the surface was corrugated into three bands to accommodate straight corrugations; the bands were separated somewhat at ±12°. For the antenna raised to height 0.19 wavelength, the reflectances for the two surface configurations are virtually identical; see Figures 5-12 and 5-13. The periodic variation is absent in Figure 5-13 for the corrugated surface.

5.4 Depth Dependence

The depth of a buried object influences the sturcture and magnitude of the field that is reflected when the object is illuminated. Some experiments were done to estimate the influence of depth.

Measurements were made with apparatus arranged as in Figure 5-9. The antenna was scanned over a circular arc. The scattering object was a 12 inch square aluminum plate. The plate was buried at severl depths ranging from 0 inches (on the surface of the soil) to a maximum of 8 inches

Figure 5-14 shows reflectance at the peak of the intensity pattern; the peaks were over the center of the object. Patterns were symmetric for all depths, indicating that the plate was level. The reflectance ranged from -3 dB to -16.5

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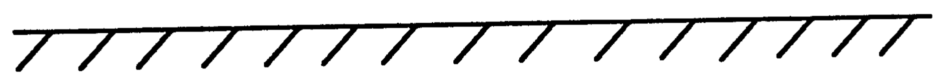
* L was thus 0.18 wavelength.

** For the corrugated surface, height was measured from the mean height.

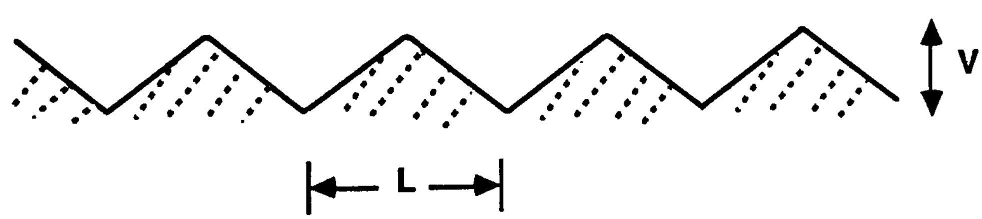
dB. The reflectance with the object absent was -19.6 ±1 dB.

Figure 5-14 also shows the width of the reflectance pattern to the first nulls. This observed width ranged from 11 1/2 to 29 inches.

Clearly the width and the peak intensity of the reflectance pattern vary. These variations have implications for processing methods that attempt to recognize mines by comparing measured data with stored data measured earlier for known mines. Section 8 discusses processing further.

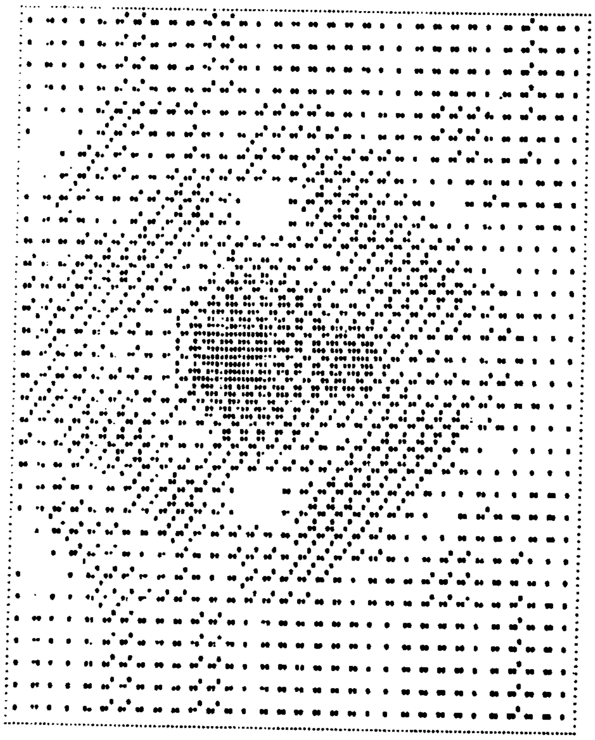


(a) Smooth

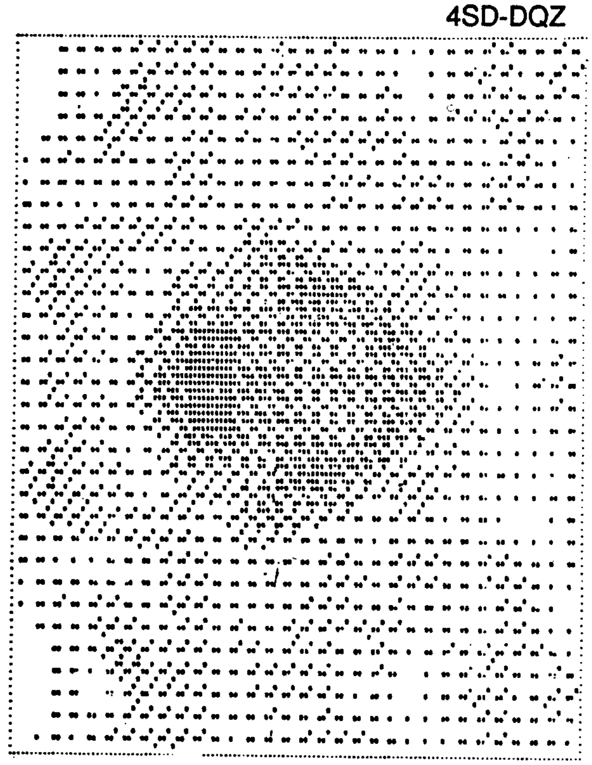


(b) Grooved

Figure 5-4. Surface Configurations



Measured, Hologram



Image

Figure 5-5. Measured Intensity of Hologram and Computed image for Foam Block With Antenna Four Inches Above Smooth Soil Surface

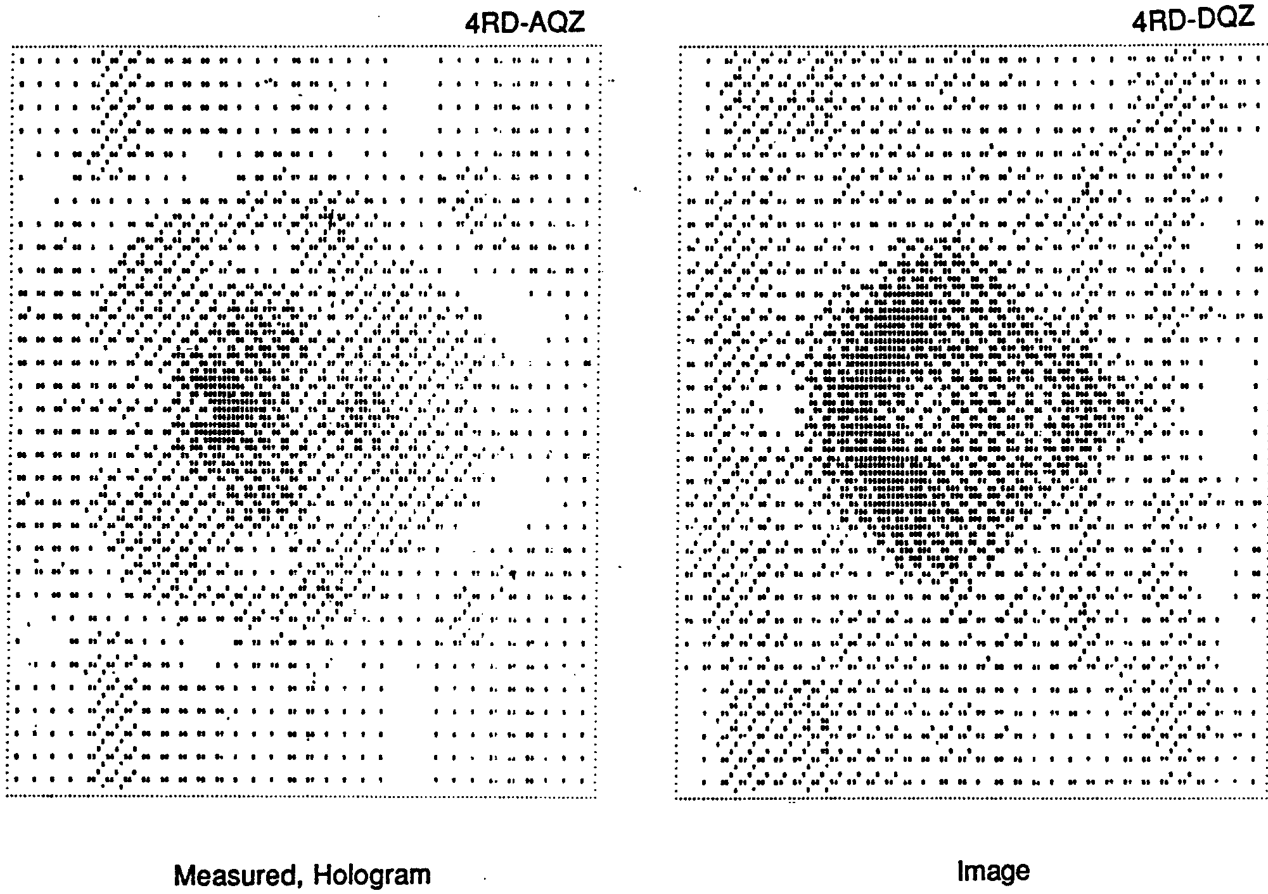
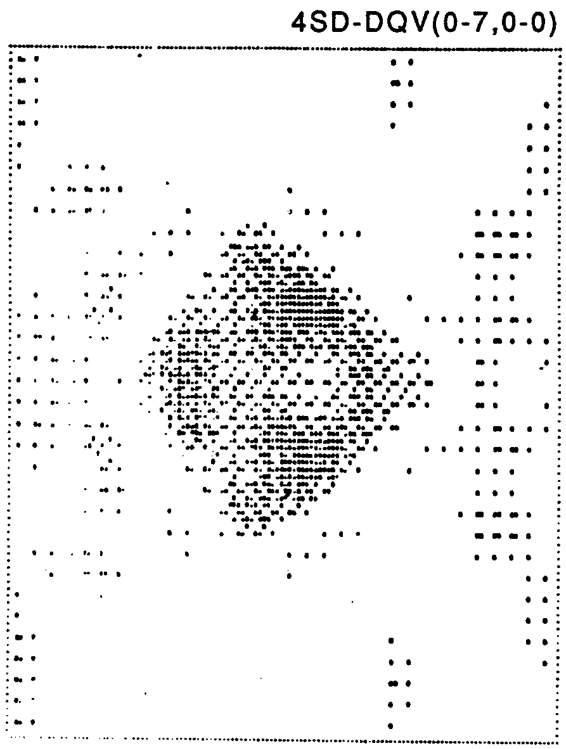
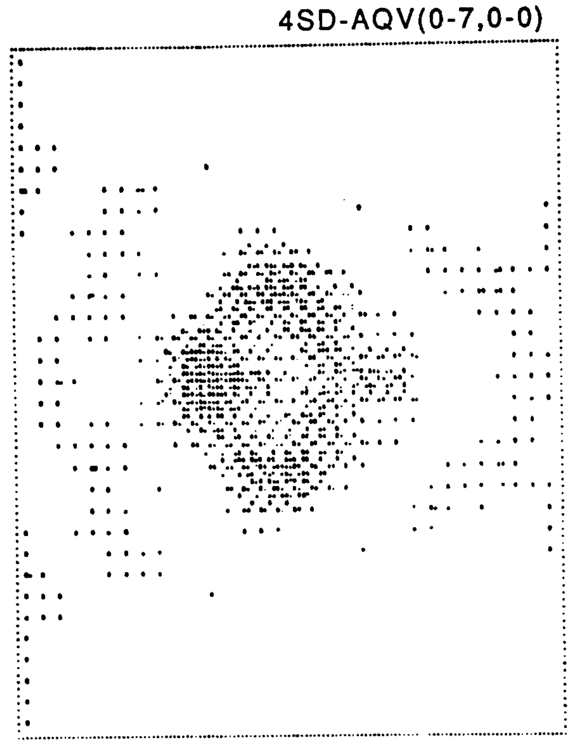


Figure 5-6. Measured Intensity and Hologram for Foam Block With Antenna Four Inches Above Mean Height of Grooved Surface



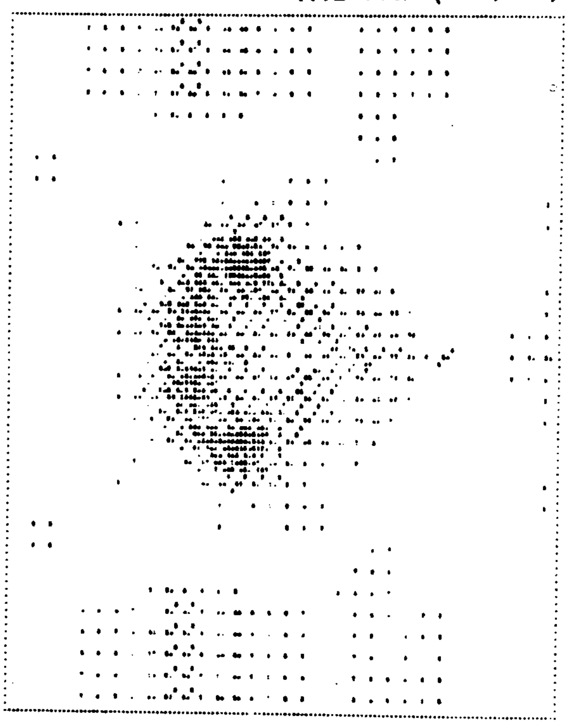
Measured, Hologram



Image

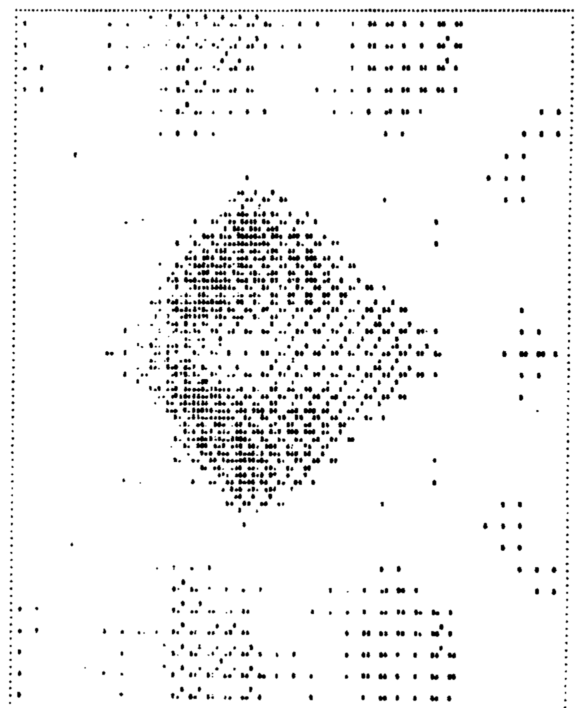
Figure 5-7. Intensity in Hologram and Image For Foam Block With Antenna Four Inches Above Smooth Surface. The Hologram Data Were Modified By Subtracting a Complex Valued Background Obtained in the Region Away From The Object.

4RD-AQV(0-6,0-0)



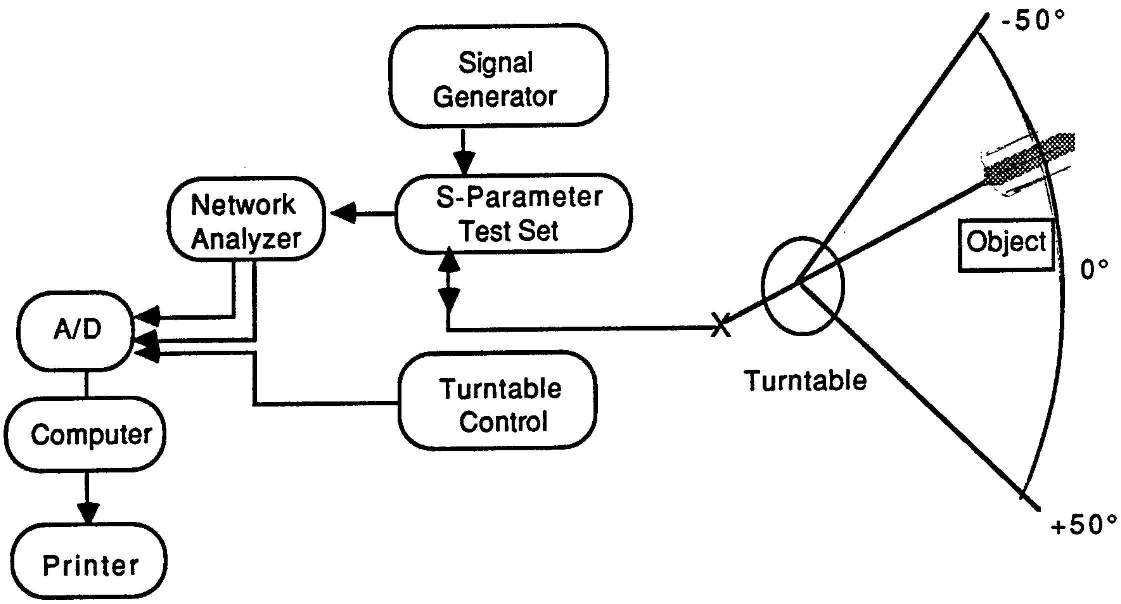
Measured, Hologram

4RD-DQV(0-6,0-0)

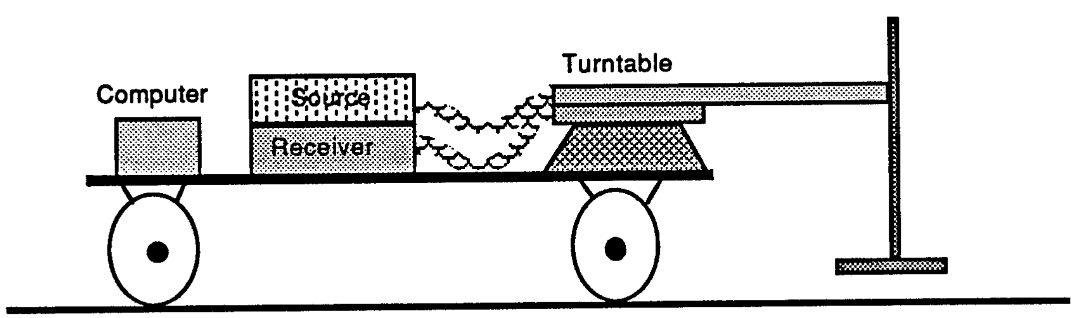


Image

Figure 5-8. Intensity in Hologram and Image For Foam Block With Antenna Four Inches Above Grooved Surface. Hologram Data Were Modified by Subtracting the Background.



(a) Block Diagram



(b) An Arrangement of Equipment on a Cart.

Figure 5-9. Test Setup

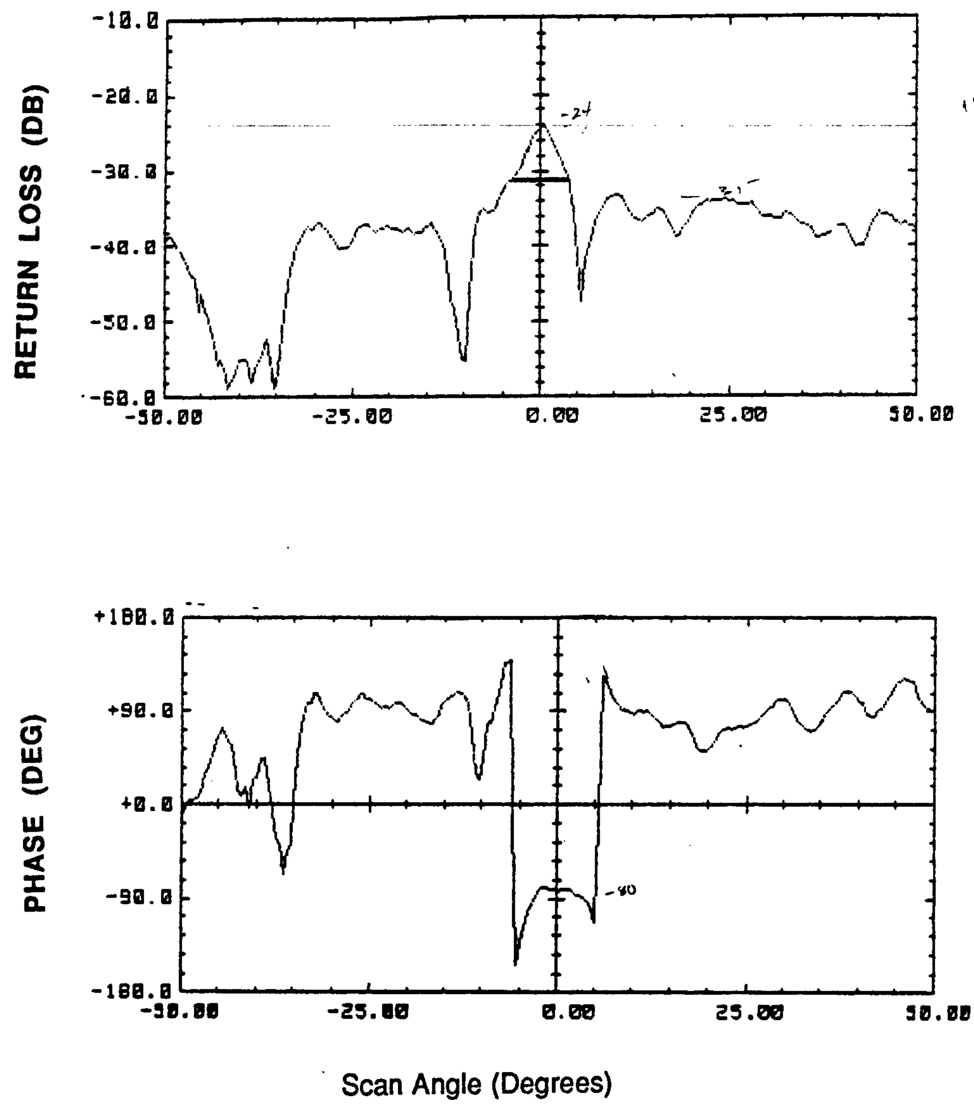


Figure 5-10. Reflectance for 12" Square Teflon Block at 2" Depth. The Horizontal Bar Near 0° Show Object Size. Antenna Height Was 0.06 Wavelength Above Smooth Sand. The Abrupt Change of Phase Near ±5° is Produced By The Network Analyzer Changing From Near +180° To Near -180°; It Is A Basis For Detection.

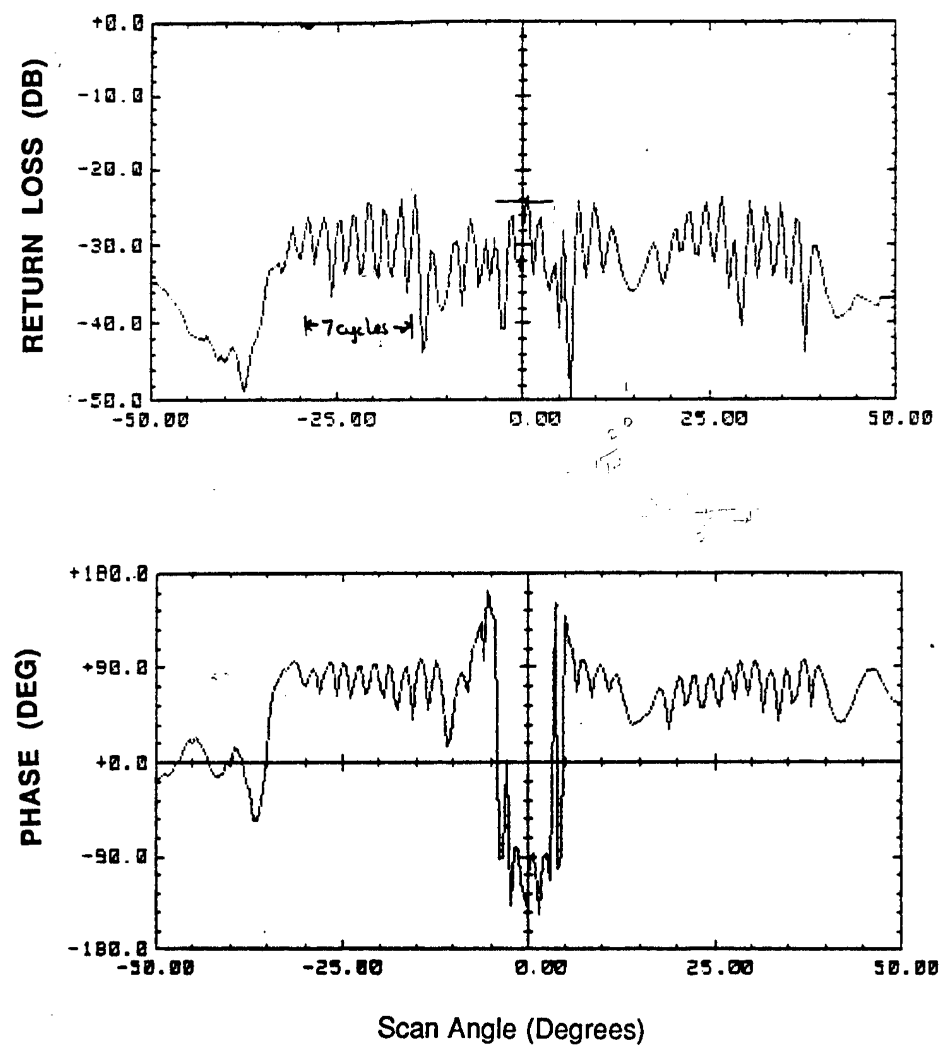


Figure 5-11. Reflectance for 12 Inch Square Teflon Block at 2 Inch Depth. Antenna Height Was 0.06 Wavelength Above Grooved Sand.

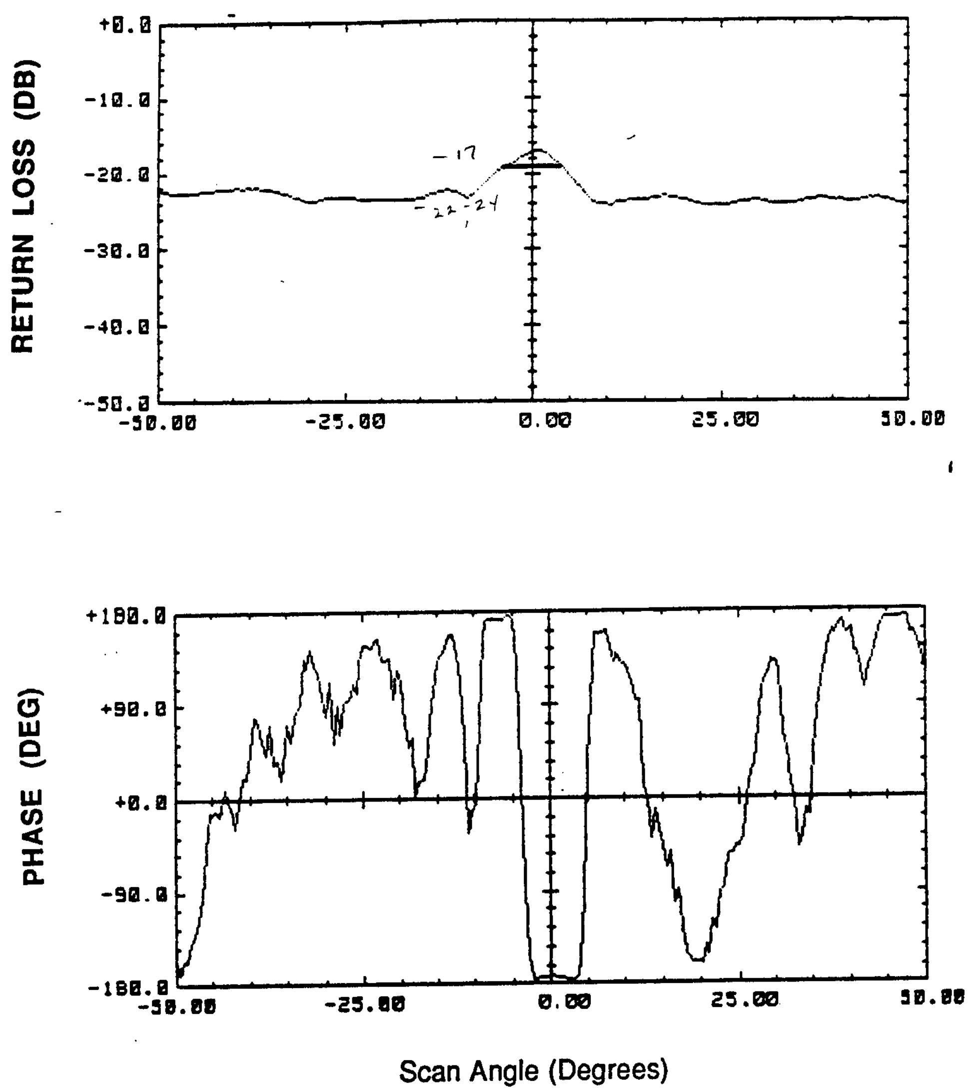


Figure 5-12. Reflectance for 12 Inch Square Teflon Block at 2 Inch Depth. Antenna Height Was 0.19 Wavelength Above Smooth Sand.

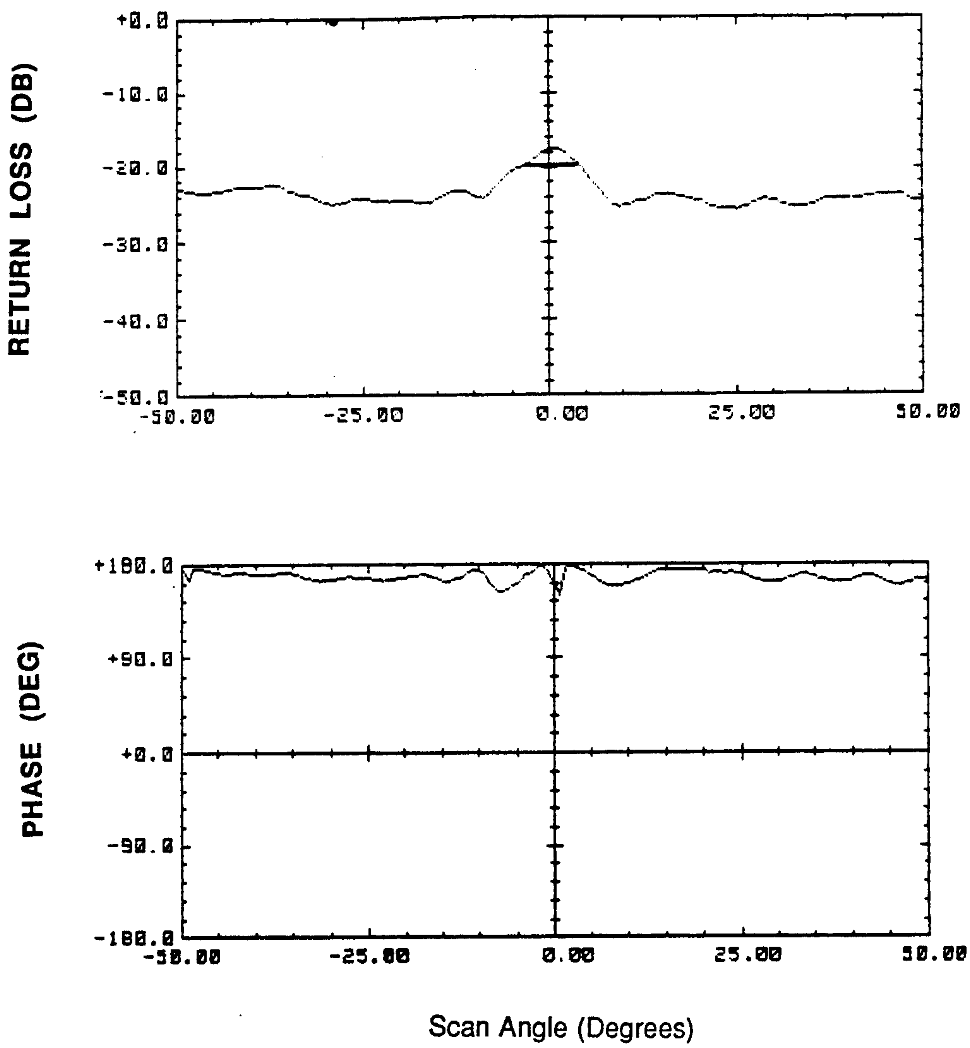


Figure 5-13. Reflectance for 12 Inch Square Teflon Block at 2 Inch Depth. Antenna Height Was 0.19 Wavelength Above Grooved Sand.

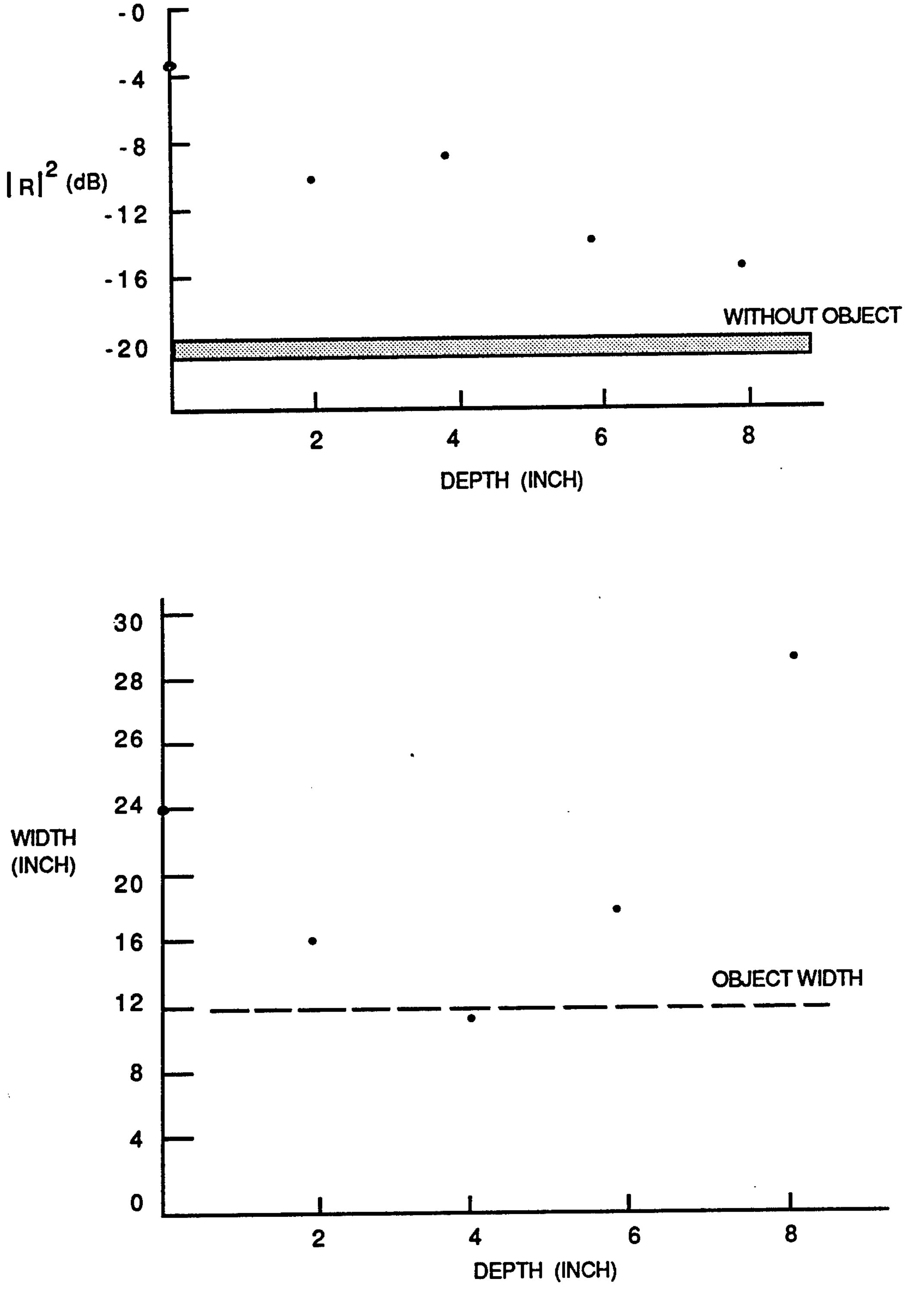


Figure 5-14. Reflected Peak Intensity and Width To First Null For Twelve Inch Square Metal Plate. Frequency: 700 MHz. Incidence Vertical. Antenna Height: 3 in; h/λ:0.18. The Reflectance Values are Normalized to Those For A Short Replacing the Antenna.

6.0 RADIATION RECEPTION

Radiation is received by antennas and transmission lines. Antennas collect energy from free space, and transmission lines guide the radio frequency waves to receivers, which are described in the next section. The present section describes antenna configurations, presents additional data on the effects of antenna height, and explains some measurement procedures and their relations to antenna configuration. Although this section emphasizes reception; it includes some material from Section 2 on radiation launching because launching and reception are coupled.

Let us amplify the distinction between monostatic and bistatic systems. In a monostatic system, one antenna both radiates and receives. The antenna is connected to a source and to a receiver by a test set or R-T unit, which is an instrument that combines power dividers into a convenient unit. In a bistatic system, one antenna radiates and another receives. The choice between the two involves comparing reflections from couplers and connectors in monostatic systems with direct radiation between antennas in bistatic systems.

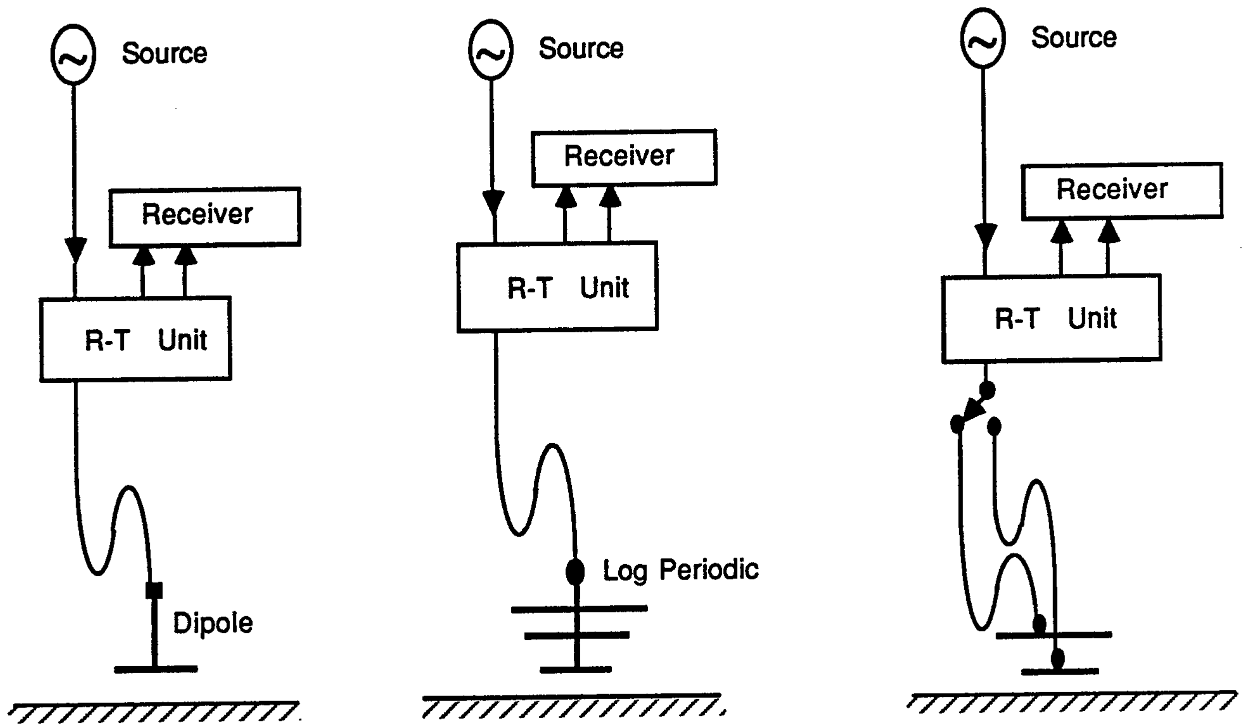
Several arrangements of receiving antennas are described in the following two subsections. Following subsections describe antenna scanning to obtain data over an area, effects of antenna height, methods for probing antenna nearfield distributions, and methods for estimating dielectric constant.

In all cases a measurement system must provide for supporting diverse antennas and adjusting their heights and positions.

6.1 Monostatic Systems

Figure 6-1 shows three monostatic arrangements.

In Figure 6-1(a), a dipole antenna is connected to a source and a receiver through a reflection-transmission unit (R-T), which directs energy to the antenna for radiation, provides a reference field to the receiver, and conducts the



(a) Monostatic
With Dipole Antenna

(b) Monostatic
With Log Periodic Antenna

(c) Monostatic
With Stacked Antennas

Figure 6-1. Three Monostatic Arrangements For Launching and Reception
In (a), a dipole is connected to the source and receiver by an R-T unit.
In (b), a log-periodic antenna has replaced the dipole.
In (c), two stacked dipoles are connected to the R-T unit by a switch.
In all cases the dipole is scanned over an area; flexible cables, without phase shift are used. In practice a computer for control and data handling is connected to the receiver.

received field to the receiver. The antenna is translated to obtain the spatial distribution of field.

Figure 6-1(b) shows the dipole replaced with a log-periodic antenna, which has greater bandwidth.

Figure 6-1(c) shows two dipoles, which operate in distinct bands, connected through switches to the source and the reflection transmission unit.

The arrangements in Figures 6-1(b) and (c) may overcome bandwidth limitations of dipole antennas as well as height variation of reception.

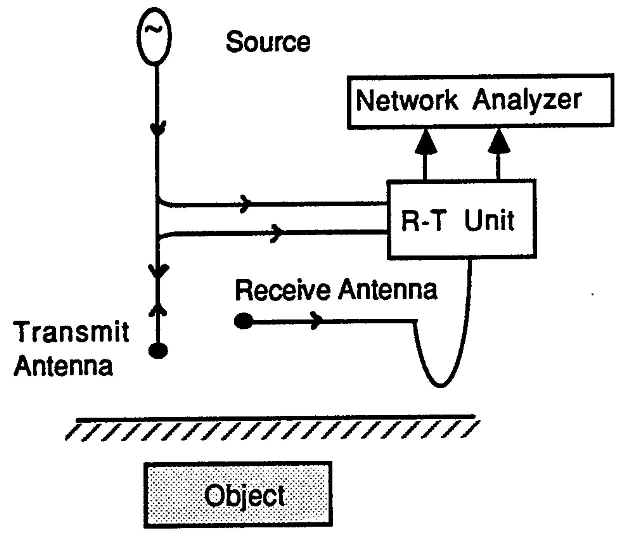
The arrangements in Figure 6-1 are practical systems; they also are building blocks of networks. For example, more antennas could be added to those in Figure 6-1(c) for more wavelength diversity, and several stacks of antennas might be used for spatial diversity, real time processing, or distributed parallel processing.

6.2 Bistatic Systems

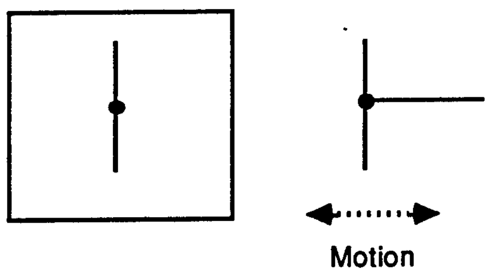
Figure 6-2 shows a bistatic arrangement; it was used to explore the field near a buried object that was illuminated by energy from a fixed transmitting antenna while a second, receiving antenna was moved over a plane to explore the field distribution.

Reference 9 describes quantitative information obtained with this arrangement. Interpretation was difficult because the object-scattered field was obscured by reflections from the air-soil interface and energy radiated directly from the transmitting antenna to the receiving, as suggested in Figure 6-3. The direct radiation can be reduced by time domain gating methods if path length differences are big enough; very narrow time windows would be necessary for low antennas because path lengths would be nearly equal. Narrow windows require broad frequency ranges so antennas may be a limitation.

Direct coupling and reflections from smooth soil can be removed by subtracting data taken with and without object; however, this appraoch is not practical for a



(a) Side View



(b) Plan View

Figure 6-2. Bistatic Arrangement for Probing the Field Near An Object. In Practice a Computer for Control and Data Handling is Connected to the Receiver.

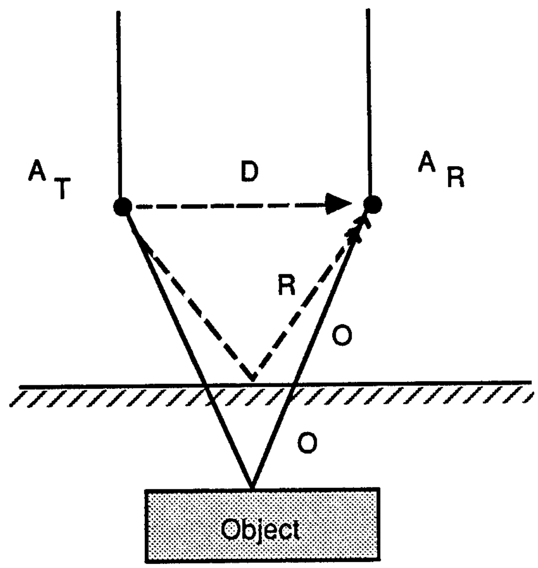


Figure 6-3. Propagation Paths Between a Transmitting Antenna A_T and a Receiving Antenna A_R . D Represents Direct Radiation; R, Reflection; O, Object Scattered Field.

mine detection system because only one scan is safely possible. Data taken where there is no mine can be stored and subtracted but statistical properties need study.

A new bistatic arrangement is described in Section 10.

6.3 Three Element Antennas With Two Kinds of Radiation Patterns

Antennas have been developed with the aim of reducing direct fields and fields reflected from smooth soil. These antennas consist of two parallel, spaced dipoles that radiate and a third, receiving dipole parallel to, coplanar with, and midway between the other two. Figure 6-4 shows the arrangement. The transmitting antennas are connected out of phase to produce a pattern with a minimum in the direction normal to the plane of the array. The receiving dipole's pattern has a maximum in the direction of the normal. Therefore, in free space direct coupling is small. When the array is over smooth and homogeneous soil, the received signal has small magnitude. A small signal is also received when the array is symmetrically located over a symmetric object; the received field increases for asymmetric positions, so the arrangement detects edges.

Systems like those in Figure 6-4 have some problems. An abrupt change in height between two flat regions can give a large reflected signal because of asymmetry. These responses are called nuisance alarms. In addition, the antenna and any balun must be precisely built; otherwise patterns are asymmetric. This statement is based on experice in evaluating AN/PRS-8 detectors, which had loaded, printed dipole antennas; detection probability for a number of simulated mines depended on pattern symmetry. The problem of nuisance alarms can be approached by imaging or by correlation methods.

In summary, three element antennas are useful because their null patterns reveal edges of buried mines by detecting two discontinuities. They also reduce reflections from soil that is not too rough. Nuisance alarms are a problem; they suggest developing recognition methods.

We have developed a new antenna that has three parallel dipoles, each in a corner reflector. The corner reflector reduces interaction with support mechanisms or the operator, a problem in the AN/PRS-8 antenna. The two outer dipoles radiate;

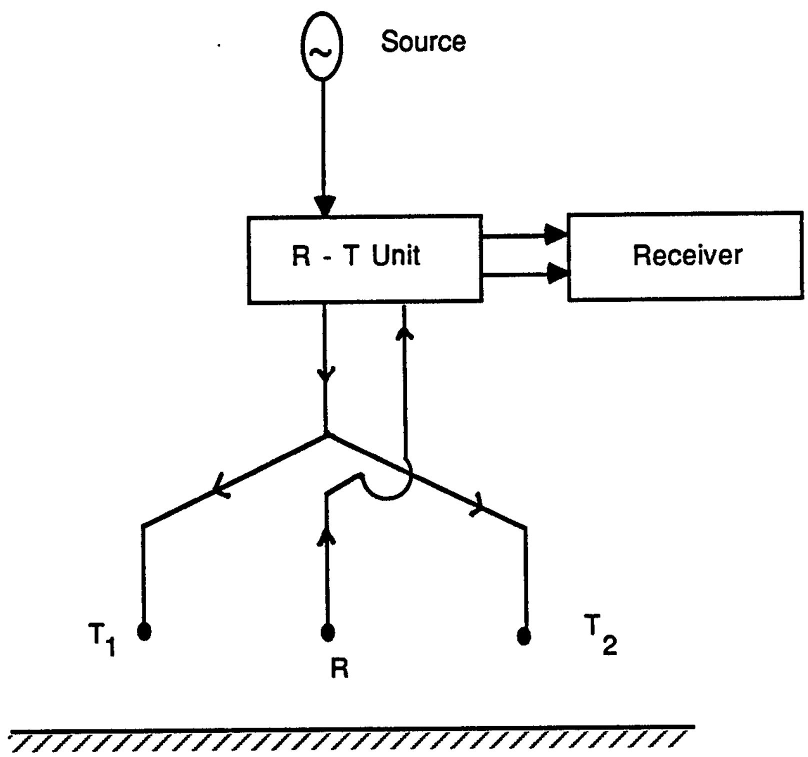


Figure 6-4. Arrangement of Two Transmitting Antennas, T_1 and T_2, and a Centrally Located Receiving Antenna R.

they are connected out of phase through a hybrid junction or impedance matched power divider. The inner dipole receives. Figure 6-5 shows the configuration, and Figure 6-6 shows a nearfield pattern measured by translating a dipole antenna on the centerline of the array for frequency 804 MHz* . The measurement setup is like that in Figure 6-2, except the tested antenna radiated toward free space.

The detection of mine edges by means of an antenna's null pattern is an example of processing by microwave hardware.

6.4 Scanning

Many mine detection methods utilize scanning, which is the lateral translation of an antenna over an arc or straight line. A typical case is the AN/PRS-8 antenna which is manually scanned over an arc. An algorithm processed and stored the signal obtained away from the mine, and signals differing sufficiently from the background were detected. We scanned an antenna over a rectangular grid to produce the microwave holograms described in Section 5.

A direct use of scanning techniques is to compare signals over an area with departures from an approximately uniform field; the departures are assumed to reveal a buried object.

Scanning can be done in many ways. The antenna can be moved along a straight path by a mechanical table or a wheeled carriage. It can be moved over an arc manually or by a turntable.

Scanning involves polarization considerations. A dipole antenna may be either aligned with or orthogonal to the scan path, as suggested in Figure 6-7. In addition, resolution of edges is greater when the antenna is orthogonal to the scan path because the field is integrated (convolved) over the antenna less than when the antenna is aligned with the scan path.

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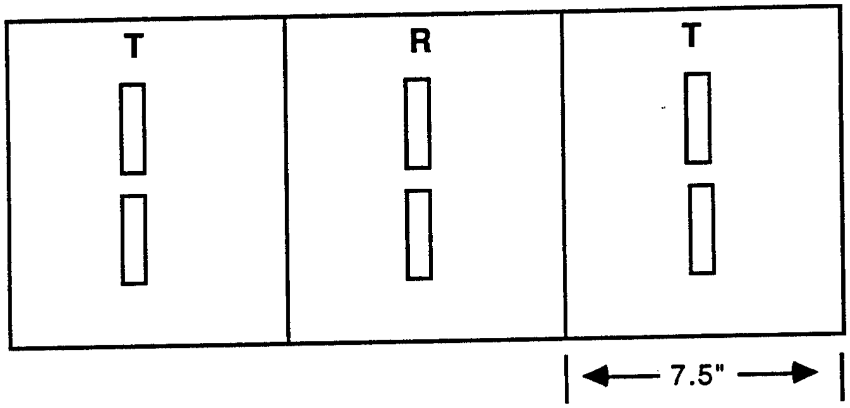
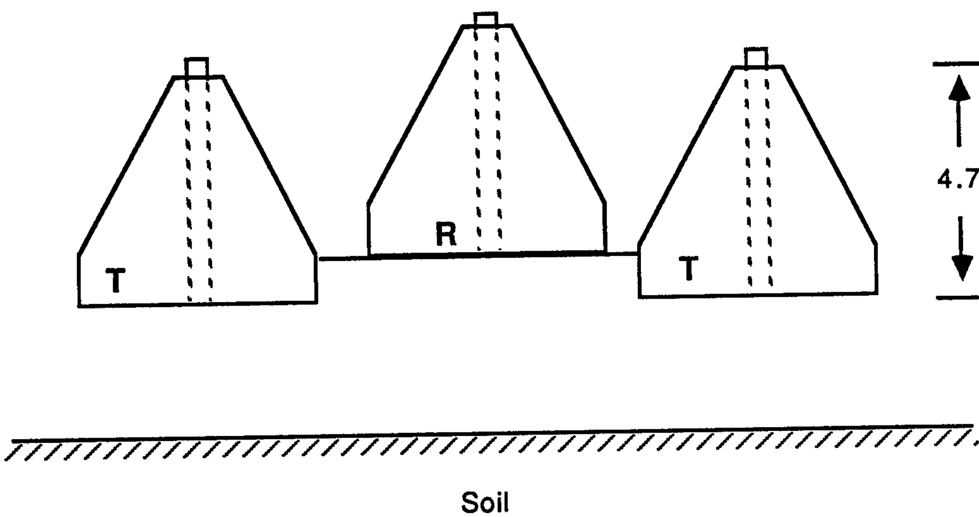
* Because this antenna contains dipoles, bandwidth is limited.



(a) Plan View



(b) Side View

Figure 6-5 Configuration of Three Element Antenna . T Designates a Transmitting Antenna; R, a Receiving Antenna. The transmitting Antennas Were Connected out of phase. Dimensions Shown are for Midband Frequency 804 MHz.

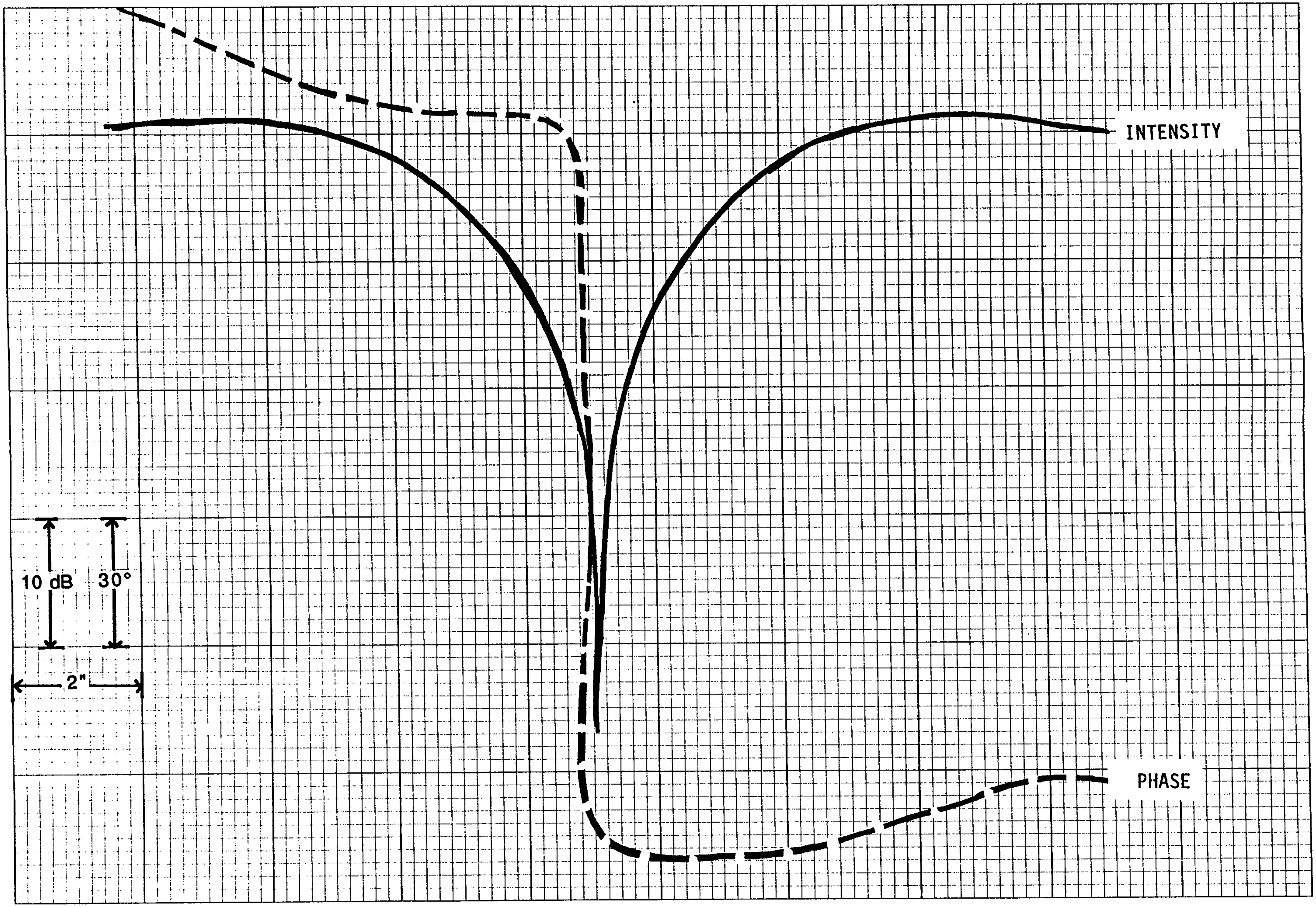
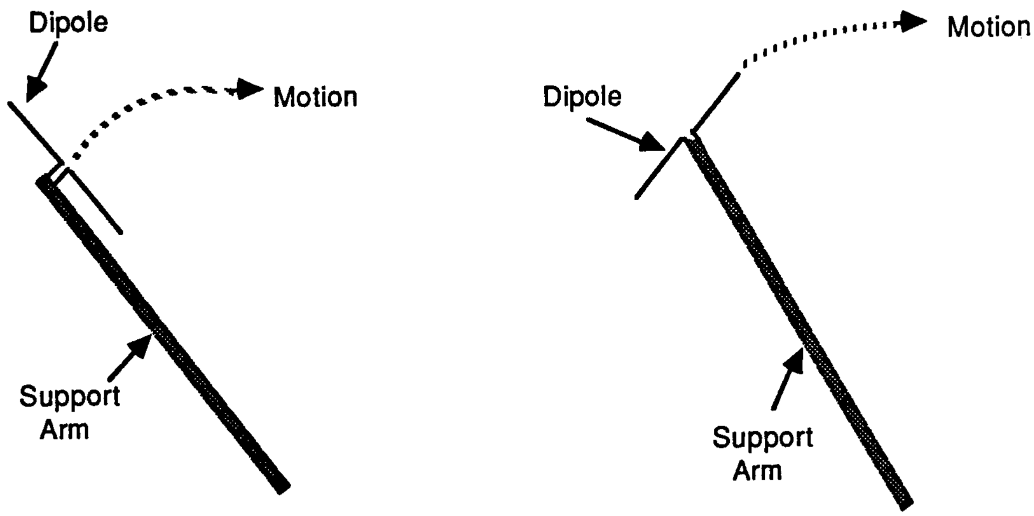


Figure [illegible]. Nearfield Plot of Transmitting Dipole Pair



(a) Antenna Orthogonal To Scanning Path

(b) Antenna Aligned With Scanning Path

Figure 6-7. Scan Paths and Two Antenna Orientations

The measurement system should have scan mechanisms. A turntable would be useful for arcs, and a cart or motor driven boom would serve for linear scans. Areas could be mapped by placing a turntable or boom on a cart. Positioners that scan rectangular coordinates are also available. The scan mechanisms must produce information on antenna positions to relate changes in reflectance to the position of a buried anomaly; servo motors or stepping motors would be used.

6.5 Height Dependence

The reflected field depends strongly on height.* Experiments show that a dependence exists for a variety of conditions including smooth and rough soil surfaces. A similar dependence also exists for buried objects. Section 5 described scattered fields for two antenna heights above smooth and grooved soil. This section gives additional data.

Measurements were made with apparatus like that in Figure 6-1(a). The apparatus was arranged as in Figure 5-9 with the antenna at a fixed position on an arc. The antenna was a dipole with a small, flat reflector. Figure 6-8 shows results; namely, the reflected amplitude for the antenna over smooth sand and for four frequencies. No buried object was present. To a good approximation all the measured values follow a common locus, when the data are plotted as a function of height to free space wavelength, h/λ. Notice the reflectance has a minimum for h/λ approximately 0.05. The reflectance increases for smaller values. For larger values of h/λ, the reflectance increases, reaches a maximum and then decreases.

We have measured very similar loci for reflectance with the antenna over the center of buried dielectric objects using apparatus as in Figure 5-9.

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* Height dependence of the field structure is a reasonable expectation on theoretical grounds as suggested in Section 5. Height dependence is observed by changing antenna height. The term height dependence will be used in reference to theoretical estimates, calculations, or experimental results; the distinction between these cases may not be important unless we are trying to reconcile theory and experiment.

The values for 900 MHz are plotted at incorrect (h/λ₀).

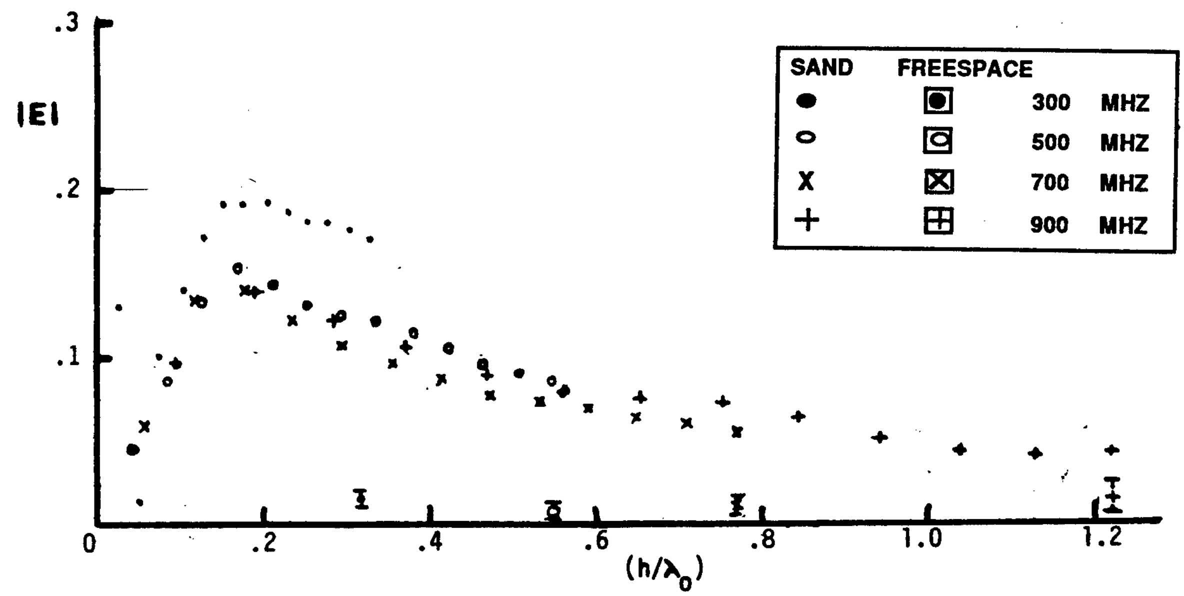

Figure 6-8. Magnitude of Reflected Field For Sand. The Bars Near the Horizontal Axis Show the Range of Reflections for Radiation Into Free Space.

We conclude that a measurement system should have a mechanism for adjusting antenna height. An automatic sensor and height adjustment mechanism would be useful in measurements over a rough soil; development is necessary.

6.6 Dielectric Constant Estimation

Soil dielectric constant κ_S can be estimated from reflectance of smooth soil by using the formula for Fresnel reflectance, where reflectance is

$$r = (1 - \sqrt{\kappa_S}) / (1 + \sqrt{\kappa_S}). \tag{6-1}$$

Dielectric constant can also be estimated from reflectance measured from a large buried metal plate. Phase change with frequency can be related to the index of refraction, where phase is $2\pi d\sqrt{\kappa_S}/\lambda$.

Precautions include adequate antenna height and plate size exceeding a few wavelengths.

6.7 Antenna Nearfield Measurement

The system should be able to measure nearfields for several reasons. Nearfield data have been useful in evaluating the effects of antenna asymmetries on detection probability of detectors; see Reference 6. Nearfield data indicate the size of an illuminated region and phase properties; this kind of information may be useful in developing processing methods, developing new antennas, or evaluating existing antennas. We define the antenna's nearfield region as a volume with minimum dimensions at least as large as the antenna's largest dimension.

Let us first consider nearfields in free space; that is the antenna is oriented so the soil has no influence. Later on we consider nearfields when an antenna radiates toward the soil.

The apparatus for nearfield measurements includes a source, receiver, and R-T unit as in Figures 6-l and 6-2* . *Therefore, the measurement system could*

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* Figures 6-l and 6-2 omit a computer for control and for data processing.

evaluate fields scattered by buried objects as well as antenna nearfields if suitable mechanical positioners were included.

Figure 6-9 suggests a positioning and support mechanism for nearfield measurements. The tested antenna is rigidly supported, and a probe is translated in three orthogonal directions. At our laboratory we have a precise and rigid mechanism capable of moving a probe through a 5'x5'x6' volume as well as a less expensive, portable mechanism that permits movement through a 2' cube. Microwave absorbing material should be placed on the support to minimize reflections, which cause errors.

The independent or controlled variables are rectangular co-ordinates X, Y, and Z as well as frequency. A computer would control source frequency, and by means of stepping motors, it would control probe position. The computer would also digitize and record data. The outputs would be coordinates and the scattering or S-parameters of the tested antenna. The S-parameters, which require the receiver be a network analyzer, are complex-valued reflectance and transmittance. The S-parameters would be given as functions of position for fixed frequency, or functions of frequency, for fixed position.

An antenna's nearfield distribution can be measured when it transmits or receives. A second, probe antenna scans the region near the tested antenna to measure the nearfield distribution*. By reciprocity, transmitting and receiving distributions are identical unless a fixed obstacle causes scattering to distort the field. Absorbing material is therefore necessary.

An interesting measurement is to determine reflections from the tested antenna while it transmits and the receiving probe scans. The magnitude of these reflections decreases as the separation of the antennas is increased. We have used this procedure to estimate reasonable distances for nearfield measurement.[10]

Nearfield measurements also can be made by a technique that utilizes modulated scattering. The tested antenna radiates. A scatterer replaces the probing antenna. The impedance of the scatterer is modulated, say by a diode with an applied voltage. The modulated field is received by the transmitting antenna.

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* The probe antenna can be a dipole, tuned for minimum reflections in free space

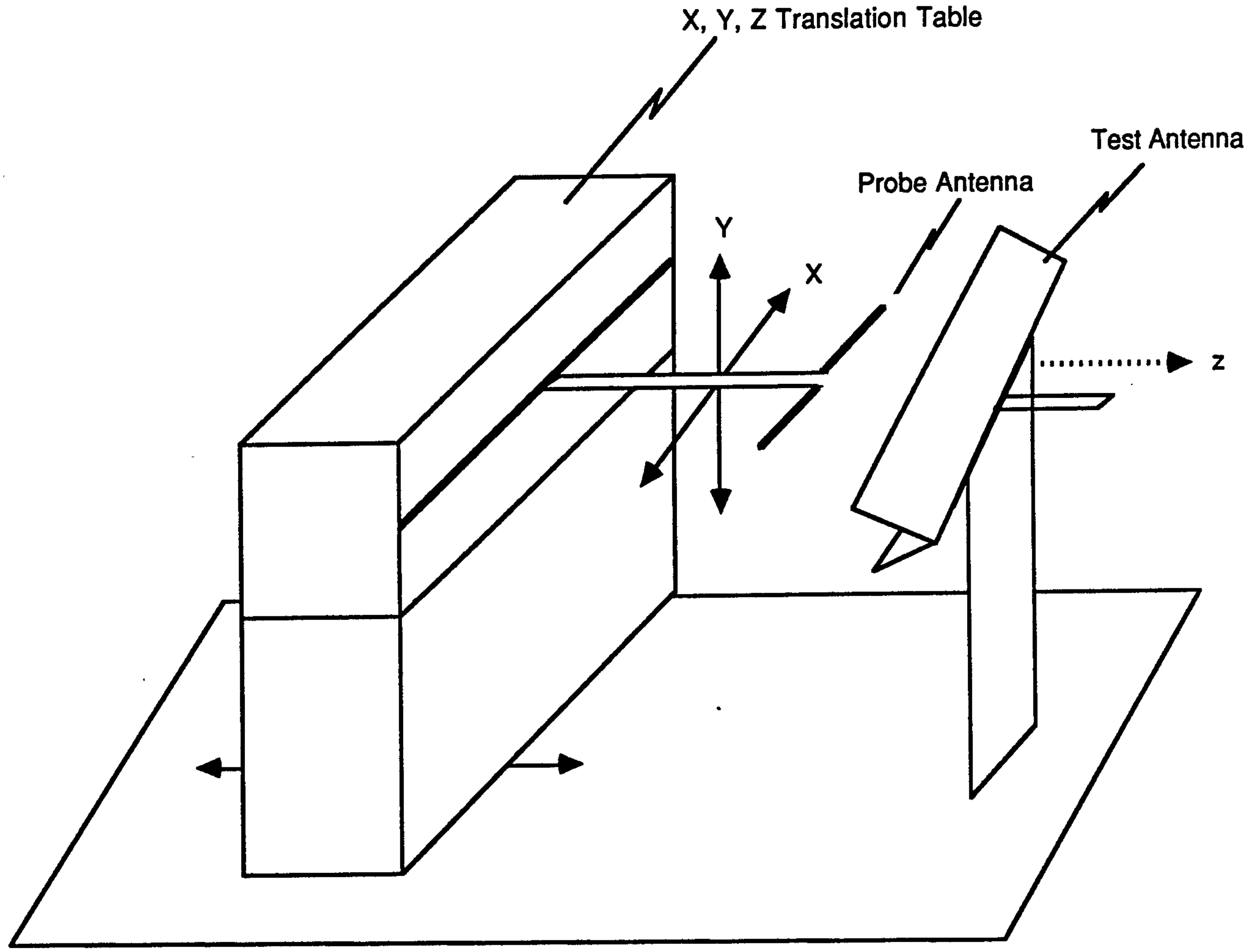

Figure 6-9. Positioning Mechanisms For Antenna Nearfield Measurement

Reflections from supports are unmodulated so they can be filtered.

The nearfield distribution is probably modified by the soil. Knowledge of the distribution near soil might be useful. Reflection measurements could be made with a modulated scatterer to identify soil reflections.* Modifications would be expected because of wavelength changes near the soil, re-radiated reflections, and the soil-reflected fields themselves.

* A modulated scatterer is a passive, scattering object such as a semiconductor device that is supplied with an alternating voltage. The applied voltage changes the scatterer's impedance so the scattered field is modulated. The modulated voltage can be detected by a narrowband receiver. The arrangement discriminates against reflections from supports and surroundings.

7.0 DETECTION: RECEIVING EQUIPMENT

7.1 Detection

The field picked up by the receiving antenna is detected by a receiver, which is indicated as item 7 in Figure S-1. The functions of a receiver are to measure intensity and phase of the received field over a frequency band.* Several commercially available receivers are described in Table 7-l. Key parameters are as follows:

- *Frequency Bandwidth.* Bandwidth is the range of frequencies that can be received. Bandwidth is necessary because mine and soil scattering depend on frequency as does attenuation. Bandwidth strongly influences cost.
- *Accuracy.* The accuracy of phase and intensity measurement clearly influences data interpretation and processing.
- *Dynamic Range.* Adequate dynamic range is needed because scattered fields vary with conditions and because antenna patterns influence received field strength.
- *Sensitivity.* Sensitivity is necessary to measure small scattered fields or possibly small constituent fields such as those that arise from roughness and add to object scattered fields and to surface reflection.
- *Cost.* The receivers differ widely in cost depending on bandwidth.

7.2 Receiving Equipment

The first receiver of Table 7-1 is a Hewlett-Packard 84l0C Network Analyzer. Maximum frequency is 18 GHz. Dynamic range is adequate, 60 dB. It has reasonable cost, $33,000. It requires an external source and test set.** It

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* Phase is necessary for describing the measured field, for constructing and testing theoritical models, and for processing data to improve detection in the presence of noise.

** A test set, sometimes called a reflection-transmission unit, is an instrument that contains couplers and power dividers; it separates incident and reflected fields and provides a reference field.

TABLE 7-1
RECEIVERS

DESCRIPTION	WEIGHT (LBS)	FREQUENCY BANDWIDTH (GHZ)	ACCURACY DB	ACCURACY DEG	DYNAMIC RANGE DB	DYNAMIC RANGE DEG	SENSITIVITY DBM	CATALOG * COST ($10^3)	SOURCE	REMARKS
NETWORK ANALYZERS:										
HP 8410C	68	.11 - 18	.08 dB per db from 0	.065 dB per dB from 0	60	360	-75	33	separate synthesized	T,R, S parameters; external source; external test set; compatible w/external computer for data storage
HP 8510T	118	.045-26.5	±0.05	±.5°	80-100	360	-80 @ 26.5 GHz	102	separate synthesized	T, R, S parameters; external source;ext test set; time domain; compatible w/external computer for data storage; programmable real time error corrections
HP 8510E	100	.045-20.0	±0.05	±.5°	80-100	360	-100 @ 250 MHz	91		
HP 8753A	68	.0003-3	±0.05	±.5°	100	360	3kHbw:-90 10Hzbw:-100	41	internal accuracy: ±.03 MHz freq ±.5 dB level synthesized source	T,R,S parameter attenuation, contains source; 1Hz frequency resolution,10 ppm accuracy; requires test set; compatible w/external comp for data storage; time domain; gating; impedance; accuracy enhancement; programmable
Wiltron 360MS18	unk	0.5-18	1° system accuracy					100	internal	T, R, S parameter
PROGRAMMABLE RECEIVERS:										
SA 1782	140	1 - 18 or 0.1 -18	±0.05 for 80 dB dynamic range	±.5°	80-100	360	-65 to -90	81		Requires SA 1773 Low Freq Converter for freq < 1 GHz

* **NOTE:**
HP 8410C - excludes $17,000 for synthesized sweeper 8341B
HP 8510E - excludes $17,000 for synthesized sweeper HP 8341B for .01 to 20 GHz
HP 8510T - excludes $55,000 for synthesized sweeper HP 8340B for .01 to 26.5 GHz
HP 8753A - Cost of a synthesized sweeper 8341B is included
SA 1782 - excludes $56,000 for SA 2185 source

does not have accuracy enhancement, a means of reducing effects of reflections, e.g. from connectors. Its accuracy has been adequate for much work, but accuracy depends on the source's performance.

The second receiver, Hewlett-Packard 8510T Network Analyzer System, has the greatest capability but is the most expensive. Maximum frequency is 26.5 GHz, which may be more than necessary. Dynamic range is beween 80 and 100 dB, depending on the external test set. Accuracy is excellent, ±.05 dB and ±0.5°, It requires an external source. Cost is $102,000 (without source). This receiver is delicate; it may not be suitable for field conditions; however, shock mounts can be utilized or subsystems can be placed in special racks.

The third receiver, Hewlett-Packard 8510E, is a new, less expensive version of the 8510T. It can be obtained in modules so it is more rugged than the 8510T. It can operate at frequencies between 0.045 GHz and 20 GHz.

The fourth receiver, a Hewlett-Packard 8753A Network Analyzer, also contains a synthesized source. It has accuracy and dynamic range equal to that of the 8510 series, but maximum frequency is 3 GHz. It is smaller than analyzers in the 8510 series and thus can be more easily protected from shock and vibration.

The fifth receiver, Scientific Atlanta 1782, was designed for measuring antenna patterns. It has accuracy equal to that of the Hewlett-Packard 8510B and dynamic range only slightly less. It contains a local oscillator, but it requires an external source. It also requires an external mixer for operation below 1 GHz. The external mixer reduces sensitivity at frequencies below 1 GHz and it complicates the arrangement of equipment. The 1782 does not measure S-parameters under computer control so operation is slow. This receiver is the heaviest of all considered. Because the instrument was designed for the special purpose of antenna testing, it is not favored for general testing of ideas for mine detection.

The sixth receiver is the Wiltron Company's Network Analyzer, Model 360MS18. It has several advantages. It contains a synthesized source. It gives system accuracy of 1° for phase measurements; this figure includes root square sum values of contributions of residual directivity of couplers, load and source mismatch, frequency response, dynamic accuracy of the network analyzer, and connector repeatability. Comparing this figure with that of other instruments is difficult because manufacturers specifications differ; however, this instrument compares favorably with the others. Despite its desireable specifications, this instrument is not recommeded because its minimum frequency is 500 MHz, which seems too high for the system that is to evaluate ideas for mine detection.

7.3 System Considerations: Recommendation

To define a system configuration, it is helpful to consider simultaneously the receiver and transmitter because the two operate together. Table 7-2 describes candidate receivers, including test sets, and a synthesized source for each. A computer must be added to provide data storage on disks and for limited data processing. Dust protection is necessary for disk drives of computers.

In summary, two alternate configurations, C and E of Table 7-2, are recommended. These configurations differ in capability and cost. Configuration E has greater bandwidth (.045 to 20 GHz) than C (0.0003 to 3 GHz). Accuracies are quite close. However the catalog cost of configuration C is approximately $45,000 compared to $112,000 for E. The restricted frequency range of configuration C seems a possible limitation in testing high frequency radar, imaging ideas, or testing propagation in soil at high frequencies. In addition; frequency domain pulse synthesis is limited by $c/2\Delta f$ where Δf is frequency bandwidth and c is propagation speed; therefore, a 2.5 GHz bandwidth would imply about 6 cm depth resolution. Configuration C is more economical than E, but E has more capability.

The instruments in configurations C and E are more easily integrated into a system than are those of the other configurations. These instruments are more accurate than those of configuration A. They are more general than those of configuration F. Configuration D is attractive, but limited to frequencies above 500 MHz. Configuration B operates up to 26.5 GHz; such high frequencies seem unncessary, and the cost is approximately $161,000.

TABLE 7-2
RECEIVER, SOURCE, AND COMPUTER OPTIONS

CONFIGURATION	ITEM	MODEL NUMBER	PHASE ACCURACY (DEG)	CATALOG COST ($$10^3$)	TOTAL COST ($$10^3$)	FREQUENCY RANGE (GHZ)	SYSTEM FREQ RANGE (GHZ)
A	Receiver & Test Set	HP 8410C	6% of measured range	33		.11 - 18	0.11 - 18
	Source	HP 8341B		40	77	.01 - 20	
	Computer	HP 9836		4			
B	Network Analyzer System inc:test set, time domain	HP 8510T	.05°	102	161	.045-26.5	.045-26.5
	Source	HP 8340B		55			
	Computer	HP 9836		4			
C	Receiver & Test Set inc:source, time domain	HP 8753	.05°	41	45	0.0003 -3	0.0003 - 3
	Computer	HP 9836		4			
D	Network Analyzer	Wiltron 360MS18	1°	100	104		0.5 - 18
	Computer	HP 9836		4			
E	Network Analyzer System inc: test set,time domain	HP 8510E	0.5°	91		.045 - 20	.045-20
	Source	HP 8314B		17	112		
	Computer	HP 9836		4			
F	Receiver	SA 1782	0.5°	81		0.1 - 18	0.1 - 18
	Source	SA 2185		56	150		
	Computer	HP 9836		4			
	Low Freq Converter	SA 1773 + Mixer		9			

The cost figures do not include costs for scanning mechanisms or storage devices. These are described in Section 9.

7.4 Sampling Oscilloscopes, An Optional Addition to the System

All of the preceding receivers are rather narrowband although some can track swept frequencies. However, they are unsuitable for very short pulses. Short pulses may be useful for identifying mines or determining depths of anomalies. If short pulse systems were tested, new Hewlett Packard oscilloscope, HP 51420A, with 20 GHz frequency range is recommended as a desireable option. Catalog cost is $28,000. A receiver of configuration C or E has much higher priority than the oscilloscope.

8.0 PROCESSOR

The processor performs two kinds of functions. One kind is in data acquisition by controlling apparatus and by digitizing, storing, and displaying measured data. The other kind is detection by processing the data. Acquisition functions are necessary for subsequent processing and for monitoring the measurement system. Clearly, the measurement system must have a computer. In contrast, processing for detection studies might be done by a mainframe computer located far from the measurement site; however, processing at the measurement site permits checking the measured data. The decision on where to do analysis depends on computer capability and algorithm complexity. A single moderate sized microcomputer can perform both functions reasonably well, but computer capacity and speed limit the complexity of detection and recognition algorithms.

This section describes several aspects of processing. The first subsection describes data acquisition; the second, identification methods that were tested or analyzed. The third gives a system view of software for detection and identification.

8.1 Data Acquisition

8.1.1 Channels

The number of data channels depends on the arrangement of apparatus.

In monostatic measurements, the system will provide phase and intensity data from the receiver requiring two channels. Antenna position data will be provided by a sensor or by computer controlled stepping motors on a positioner such as a turntable or on a cart; at most three channels are required for position data. In addition, frequency data do not require a channel if frequency changes are programmed. Therefore five channels are necessary.

In bistatic measurements, two more channels would be necessary for simultaneous measurement of reflection and transmission; the alternative is to switch cables from transmit to receive antennas and thus require only five rather than seven channels.

8.1.2 Data Sampling

For efficient data collection and subsequent processing, data should be digitized and stored on floppy or hard disks. Digital data acquisition is more suitable than analog storage on chart paper or magnetic tape.

Digital storage implies sampling. For example, sample spacing should be small; the Nyquist criterion is a guide.

Sampling implies triggering. Triggering starts and stops frequency steps in a signal source and initiates data sampling from a network analyzer or a position indicator. Triggering is usually actuated by electrical pulses.

Triggering for data collection can be done in the following ways.

- Sample as a function of time on receiving a signal from a computer. This method is suited for phase and intensity from a network analyzer.
- Sample the position of a sensor such as an antenna on receiving a signal from a computer that also controls the sensor's position.
- Sample at a fast rate, store in a buffer, and sort in a computer. This method requires a start position indicator and constant scan rates. Constant scan rates are obtained from turntables or rectangular positioning tables, but rates from carts may vary because of inertia and slippage of wheels in soil.

Sampling can also be initated by position indication of a sensor such as an antenna, supported on a positioning mechanism. The support would have a positive sensor. Continuous positions could be indicated by a servo motor that produces a ramp voltage proportional to displacement, and the ramp could be used to locate positions of phase and intensity data samples. Discrete positions of data samples can be set and digitized by a computer controlled stepping motor; this method applies to a turntable, a linearly translated boom, or a rectangular positioner.

Sampling can also be done at a constant time rate; this method assumes uniform displacement speed of sensors.

The accuracy of digital sampling depends on the analog to digital converter, which produces digitized data from the analog output voltages of instruments such as network analyzers. Typical conversion times are 10 μsec per sample.

Accuracy also depends on the number of bits; 11 or 12 give good accuracy.

To avoid errors in sampling, each sample must be acquired rapidly; the receiver bandwidth must be consistent with the scanning rate.

8.1.3 Computer Recommendation

A computer is necessary to control the signal source and sensor positioner, and to digitize and record a large amount of measured data. A computer might also perform analyses and calculations for detection algorithms.

For the measurement system we suggest a Hewlett-Packard 98580A computer. We have successfully utilized a Hewlett-Packard 9836 for control and digitization in tests at the Electronics Division and at Fort Belvoir. This computer also has been used to evaluate some detection algorithms such as those described later, in Section 8.3. the 98580A is newer and is compatible with the 9836. It has adequate storage capacity with disks, and computing speed is reasonable.

Although much can be done with present day machines like a 98580A detection systems may in the future exploit parallel processing which is discussed in another section.

8.1.4 Computer Software

Software should be written in a compiled language for relatively easy programming and speed of processing. BASIC is an interpretive language and is rather slow, but it is well suited for graphics. PASCAL is a good choice for computation because it is a compiled language supported by Hewlett-Packard.

Both, in combination, may be useful. The software should permit the following, as a minimum.

- Operation of several antennas; four or eight is a reasonable upper bound
- Sampling linear or angular position of antennas
- Sampling measured data
- Displaying measured data, phase and intensity, to permit evaluating data quality
- Store data
- Control signal source frequencies, frequency increments, bandwidth, duration of frequency, and possibly control of antenna position

8.1.5 Storage

Floppy disk drives have been very sensitive to dust in our field test experience and if used should be sealed against dust intrusion. Storage could be on a hard disk which will survive a harsh environment.

8.1.6 Mobility

The antenna's scan function is signficant. Scans over circular arcs are convenient and have interest for hand held detectors. Linear scans would be useful for vehicles, and appropriate for algorithm that utilize Fourier transforms. Both kinds should be included in the system.

The time required to measure over an area or investigate many targets depends on the speed at which the antenna is translated, or scan rate. If an antenna is moved on an arc by a boom or laterally by a linear positioner, it is more efficient to acquire data in both directions of scan. An orthogonal movement would occur between scans. Maximum scan rate will be determined by either time required by equipment to sample and digitize data or by a speed that maintains stability of the antenna system. Arrays of several antennas can accelerate data acquisition.

Another aspect of mobility is antenna height. A height sensor can send data to a computer to control antenna height.

8.2 Detection and Identification Methods

Many approaches exist for detecting and identifying buried mines. Several were studied during the project.

A simple approach is to look at a display of measured phase or intensity for a single arc scan of an antenna. Phase and intensity would be relatively smooth functions of position if the antenna does not illuminate a buried object. Departures from a background level would suggest a buried object. This approach does not identify an object by determining shape; rocks and roots can be mistaken for mines; moreover, the reflection from the air-soil interface obscures the field scattered by the buried object. Identification might be improved by studying data from several adjacent arc or linear scans. Object shapes can be estimated; for example, roots give elongated field perturbations. Our experience shows that roots are more easily detected when they are aligned with the field rather than when they are orthogonal. Resonant scattering might be identified by observing frequency dependence. Simply looking at measured data seems inadequate because diffraction spreads the scattered field so the lateral extent of a phase or power variation differs from the size of the buried object.

Processing seems crucial for mine detection.

The remainder of this subsection describes some processing methods that we applied. The methods include direct processing of measured data, image formation, gradient and correlation. In addition, a form of pattern recognition was considered qualitatively

8.2.1 Sobel Edge Enhancement[11]

This form of processing forms differences between measured reflectance values for adjacent samples. The differences are similar to numerators of difference quotients, which in the limit are derivatives. The processing gives slopes so it is a method for enhancing edges in images. Edges indicate object size. This form of processing is simple and fast. It can be used for a single arc or several adjacent arcs, and it can be applied to phase, intensity, or complex-valued data.

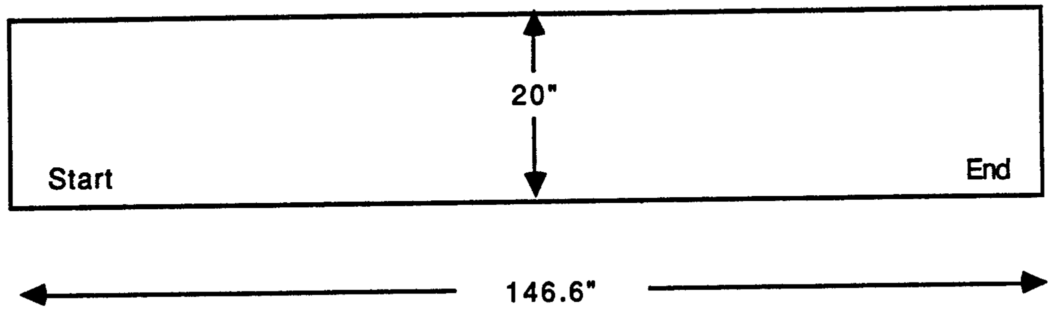
We have used the Sobel method to process data measured in our mine lane. One example was a buried Teflon cylinder, six inch diameter and two inches thick; its top surface was two inches deep in sand. Frequency was 815 MHz. The three element antenna of Figure 6-5 was scanned by a boom of radius 84 inches on 21 arcs spaced by one inch; because the scans spanned 100°, each arc had length 146.6 inches. The soil surface was smooth.

Before presenting some results let us explain the computer graphic presentation. Data are measured over a set of arcs that span 146.6 inch laterally and 20 inch longitudinally, but for simplicity data are presented as straight lines on the computer driven display. Figure 8-1(a) shows a rectangle that bounds the measured data. The rectangle is divided into four sections as in Figure 8-1(b). Three sections have length 46.7", one has length 5.8". The data of the last, 5.8" wide, rectangle are omitted. The three, 46.7" wide rectangles, are stacked to make the display compact; see Figure 8-l(c). The data start in the upper left region proceed to the right until reaching the right edge; the data continue in the central rectangle in the same pattern and continue into the third, lowest rectangle. Both measured and computed data are presented in the format of Figure 8-1(c).

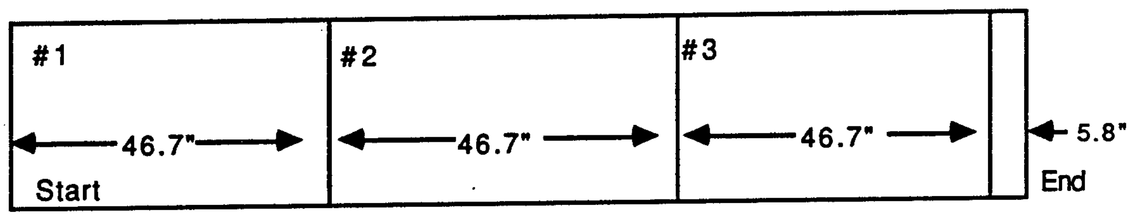
Figures 8-2 and 8-3 show measured phase and intensity for a 6 inch square diameter, 2 inch thick Teflon cylinder buried in sand. Figure 8-4 shows computed values after applying the Sobel operator to the complex data in Figure 8-2; subsidiary amplitude peaks are reduced. Figure 8-5 shows the result of squaring the Sobel output of Figure 8-4; subsidiary amplitude peaks are greatly reduced. Figure 8-6 shows the Sobel operator result when only intensity of Figure 8-2 was processed; Figure 8-7 shows the result after squaring.

The numerical method for computing the Sobel edge enhancement transforms is as follows.

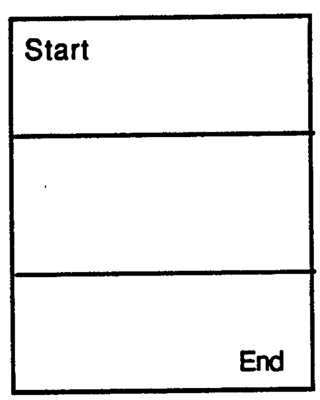
The input data is a rectangular array matrix M_{ij} , whose indices i and j vary from 1 to some numbers N and M respectively. The output data is the Sobel transform, also an array S_{ij} whose indices i and j vary from 2 to N-1and M-1, respectively. Next, defined three arrays:



(a) Measured band of data; the measurements are made over circular arcs, but presented as rectangular to simplify a computer driven display.



(b) Subdivision of data into four subsets.



(c) Stacked rectangles.

Figure 8-1. Arrangement of Data for Sobel Processing

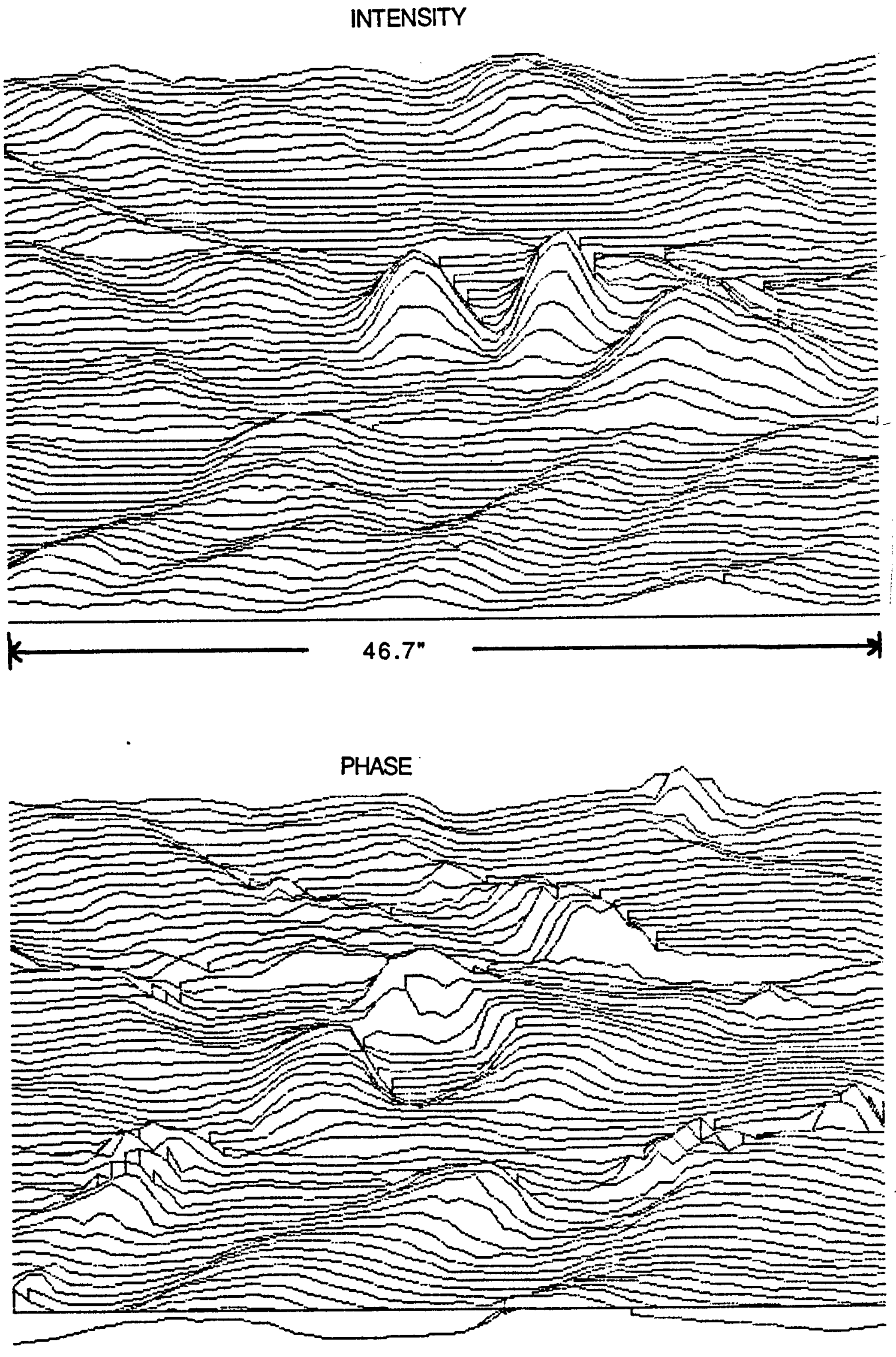


Figure 8-2. Measured Intensity and Phase for a Teflon Cylinder, Diameter 6", Thickness 3", Antenna Height 3". Intensity Values From 0 to 93.75 Arbitrary Units. Phase Range From -180° to 180°. Sand Surface Was Smooth.

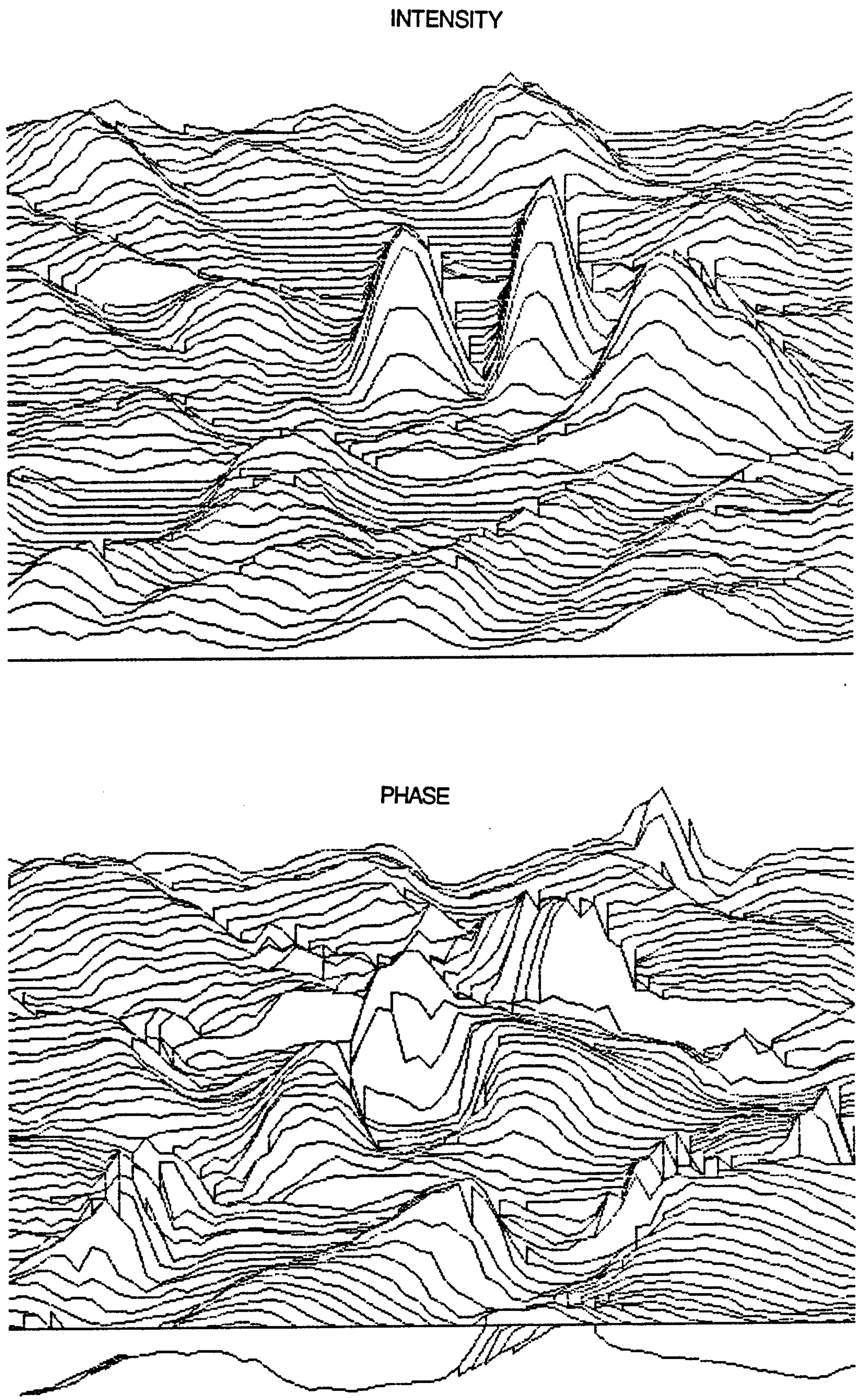


Figure 8-3. As in Figure 8-2, But Vertical Scales Doubled.

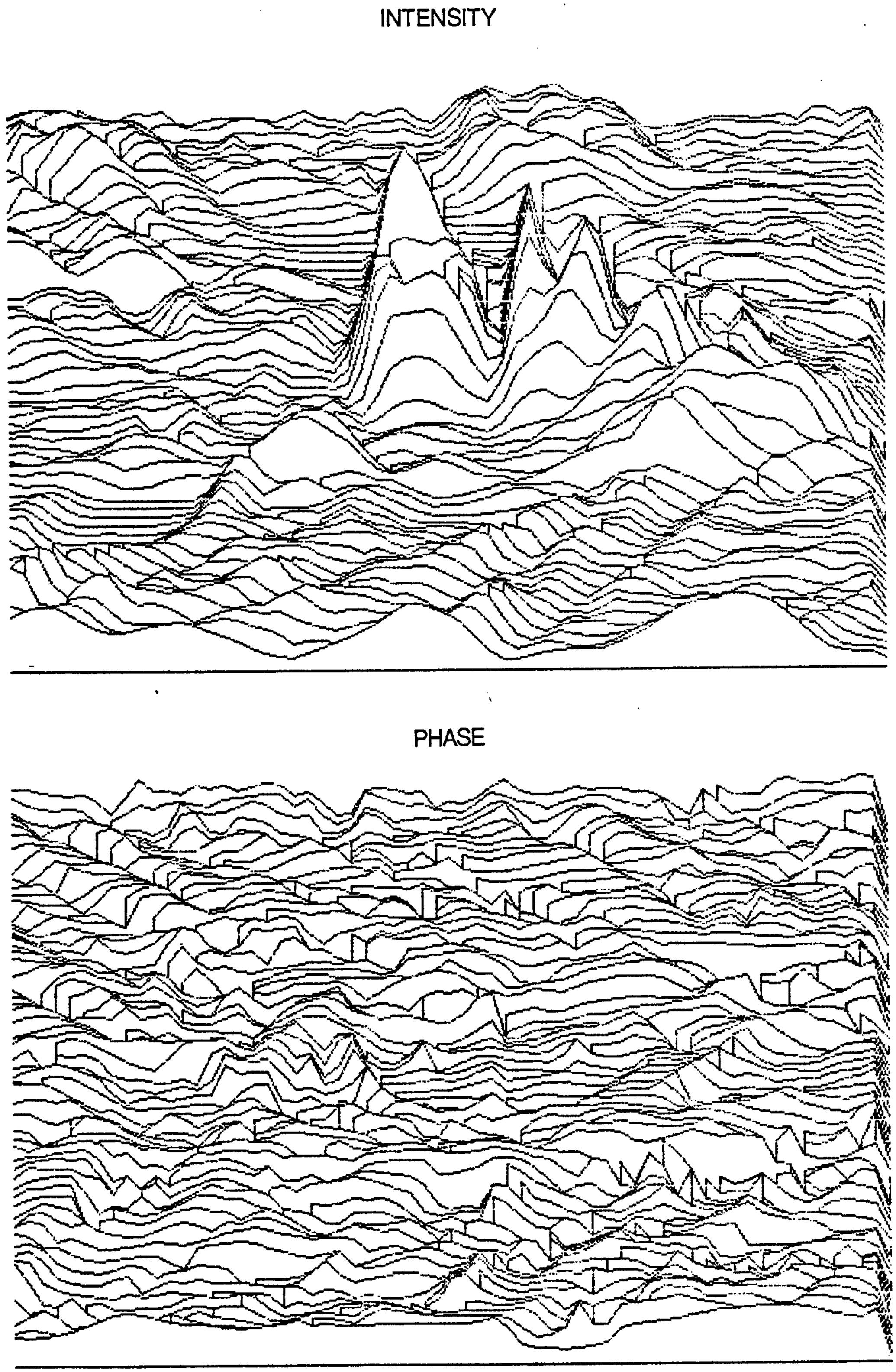


Figure 8-4. Computed Intensity and Phase of Sobel Transform for Data in Figure 8-2. Peak Amplitude is 33.5.

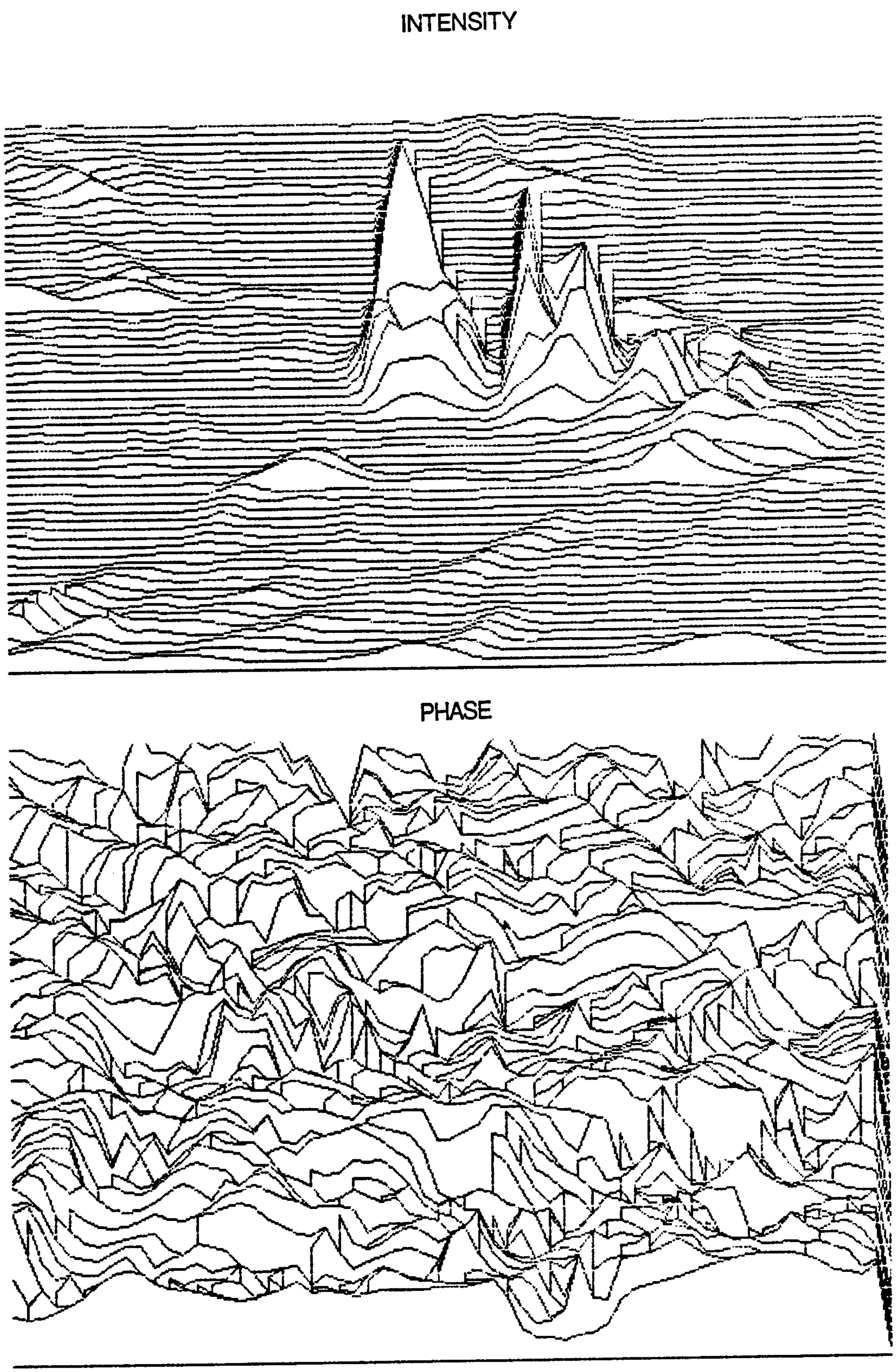


Figure 8-5. Squared Values of Result in Figure 8-4.

INTENSITY

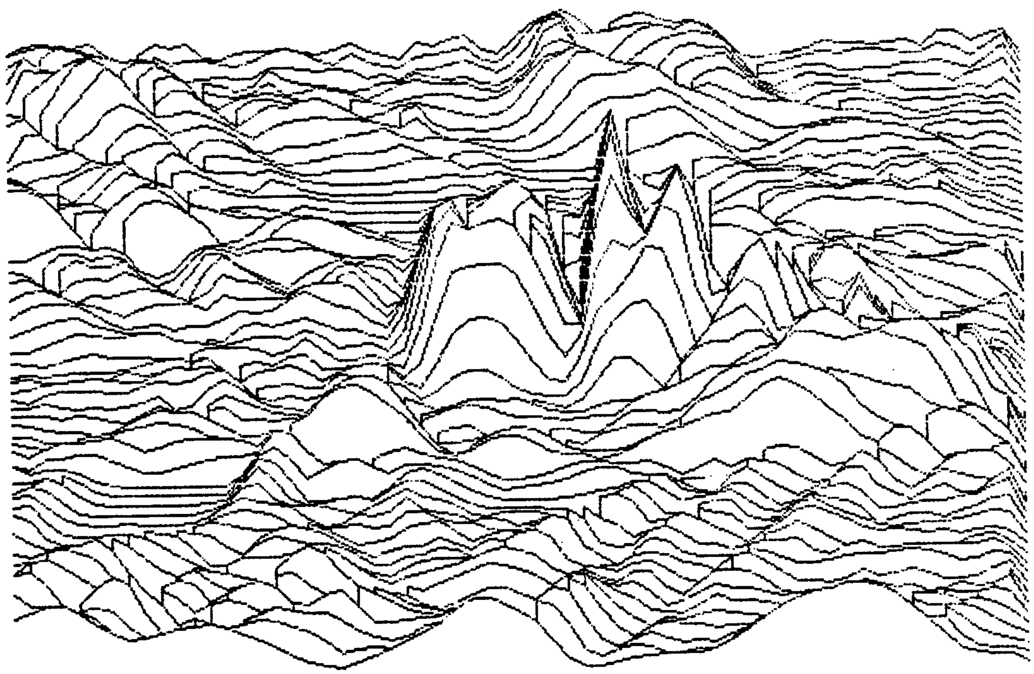


Figure 8-6. Sobel Operator Output for Intensity Only of Figure 8-2 Input.

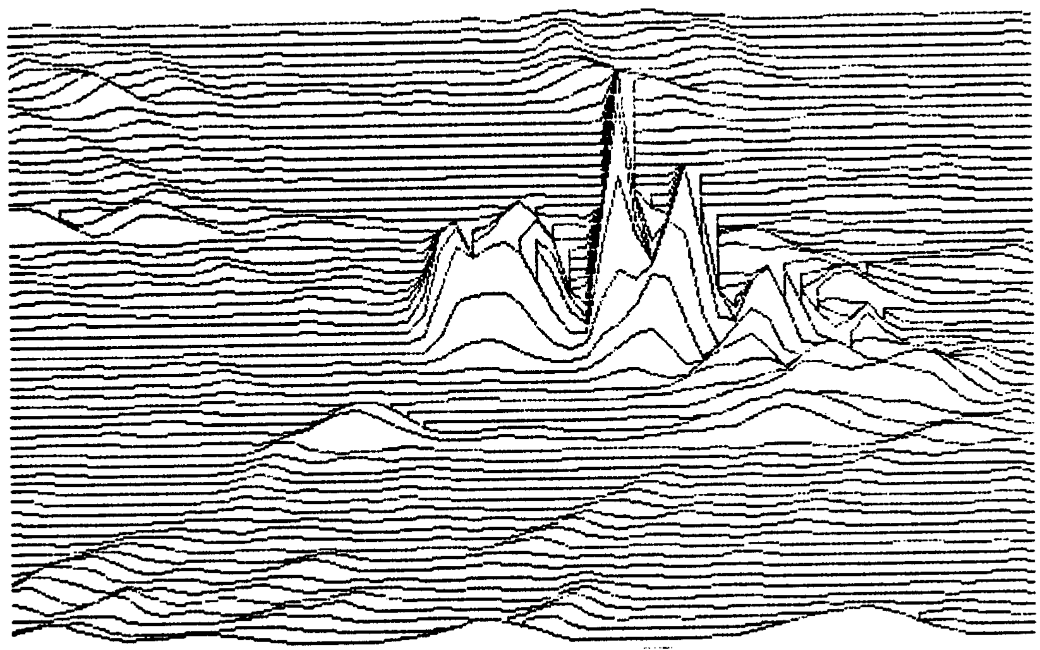


Figure 8-7. Squared Values of Figure 8-6.

$$X = \begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix} \qquad Y = \begin{pmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{pmatrix}$$

and

$$L_{ij} = \begin{pmatrix} M_{ij,\ j-1} & M_{i,\ j-1} & M_{i+1,\ j-1} \\ M_{i-1,\ j} & M_{ij} & M_{i+1,\ j} \\ M_{i-1\ j+1} & M_{i,\ j+1} & M_{i+1,\ j+1} \end{pmatrix}$$

The Sobel transform is computer by:

$$S_{ij} = \sqrt{(L_{ij} \cdot X)^2 + (L_{ij} \cdot Y)^2}$$

Where • denotes the dot product of the two matrices. Note the quantity under the radical is a number, not an array.

A variation is the Sobel squared transform, which has

$$S_{ij} = (L_{ij} \cdot X)^2 + (L_{ij} \cdot Y)^2 \quad .$$

If M_{ij} is real (such as magnitude only values) then L_{ij} is real and S_{ij} is real. If M_{ij} is complex, then X, Y, L_{ij}, and S_{ij} are all complex.

8.2.2 Phase Switched Interferometer

This approach is based on an interferometer that was developed for radio astronomy by Ryle.[12] Two antennas are alternately switched between in-phase and out-of-phase conditions. The outputs are multiplied and averaged in an amplifier. This approach removes smooth background from interference fringe patterns.

We have applied a form of this processing to buried object detection and to both smooth and corrugated soil.[13] The method reveals edges, because it utilizes differences. However, it was limited in smoothing severe fluctuations of intensity in fields reflected from corrugated soil.

The formulation is shown in Figure 8-8. The measurement with one antenna yields E(x). We form H(x,s), where s is sampling interval;

$$H(X,S) = [E(X) + E(X + S)] \; [E(X) - E(X + S)]^*$$

For smoothing, utilize

$$G(X_C, S) = \int_{X_C - A}^{X_C + A} H(X,S) \, dX$$

where the integration is over a path of length 2A.

The measured data of Figures 5-10 through 5-13 were processed. The object was a Teflon block, 12 inch square x 3 inch thick buried two inches below the surface of smooth sand. Frequency was 700 Mhz.

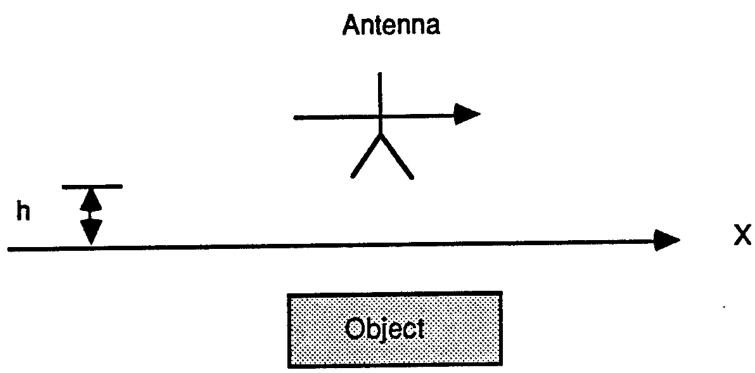
Figures 8-9 and 8-10 show H(X,S) for two values of S for height 0.06λ. The measured data are in Figure 5-10. Figure 8-9 for S equal 3.8 inch has two power maxima separated by 3.1°, which corresponds to 4 1/2 inch; recall the object width was 12 inch. In Figure 8-10 for S equal 0.76 inch the power is not divided into two distinct maxima.

Figures 8-11 and 8-12 show H(X,S) for height 0.19λ, again for smooth sand. The maxima in Figure 8-11, for S equal 0.76 inch, are spaced by 11.9 inch, which compares well with the block's 12 inch width. Figure 8-12 shows some fluctuation is introduced by the large value of S.

Integration of data in Figure 8-9 to yield $G(X_C,S)$ slightly increased peak spacings; see Figure 8-13. In this case integration changed peak separation negligibly and H(X,S) was smooth to begin with.

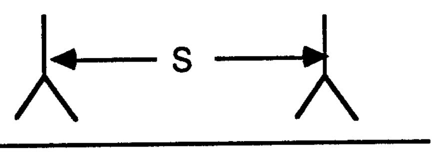
Now consider corrugated sand. Figures 8-14 and 8-15 show H(X,S) for h/ equal 0.06 for S equal 0.76 inch and 3.8 inch. The location of the object cannot be discerned. In contrast for h/λ equal 0.19, S equals 0.76 inch, Figure 8-16 shows a large correlation peak at the object's location. Although the two edges are not apparent, object location is.

Integration of the data in Figure 8-15 to evaluate $G(X_C,S)$ produces a small improvement over the data for h/λ equal 0.06λ. See Figure 8-17, and compare it to Figure 8-15.



(a) Measurement: Phase, Intensity With Displaced Antenna; E(X)

$$H(X,S) = [\,E(X) + E(X+S)\,]\,[\,E(X) - E(X+S)\,]^*$$



$$G(X_C, S) = \int_{X_C - A}^{X_C + A} H(X, S)\, dX$$

(b) Calculate

Figure 8-8. Formulation for Phase Swiched Processing

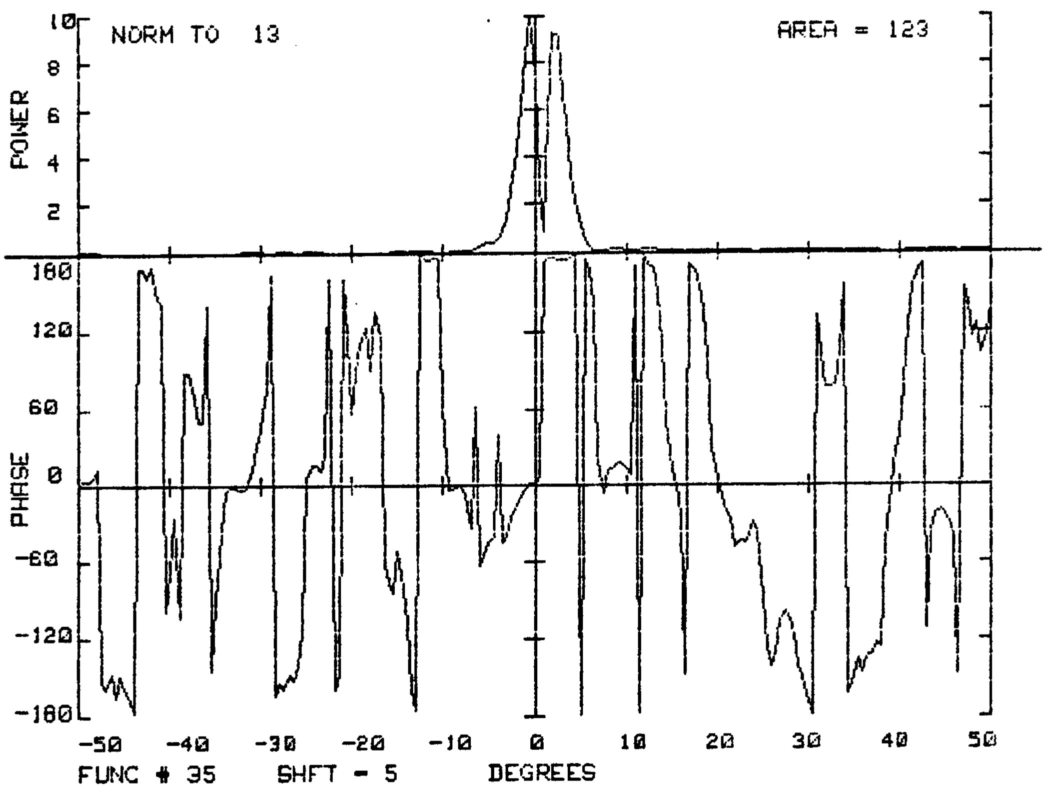


Figure 8-9. H(X,S) for Teflon Block Buried 2" Deep in Smooth Sand. Antenna Height - 0.06λ ; S = 3.8".

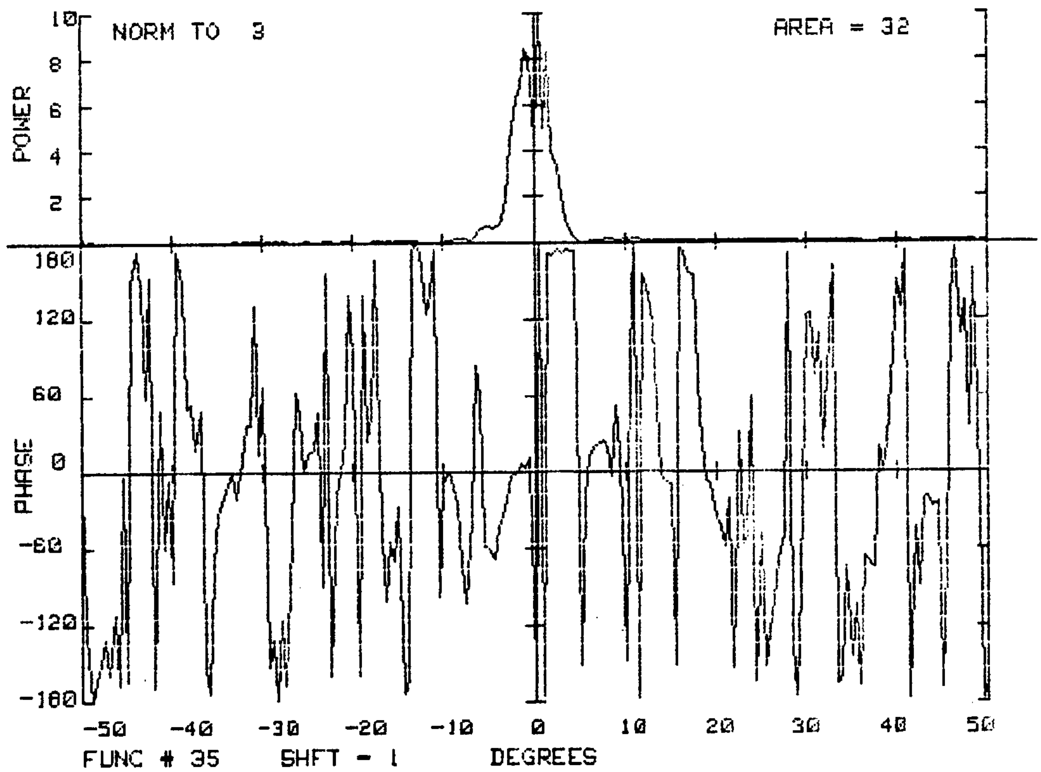


Figure 8-10. As in Figure 8-9, but S = 0.76".

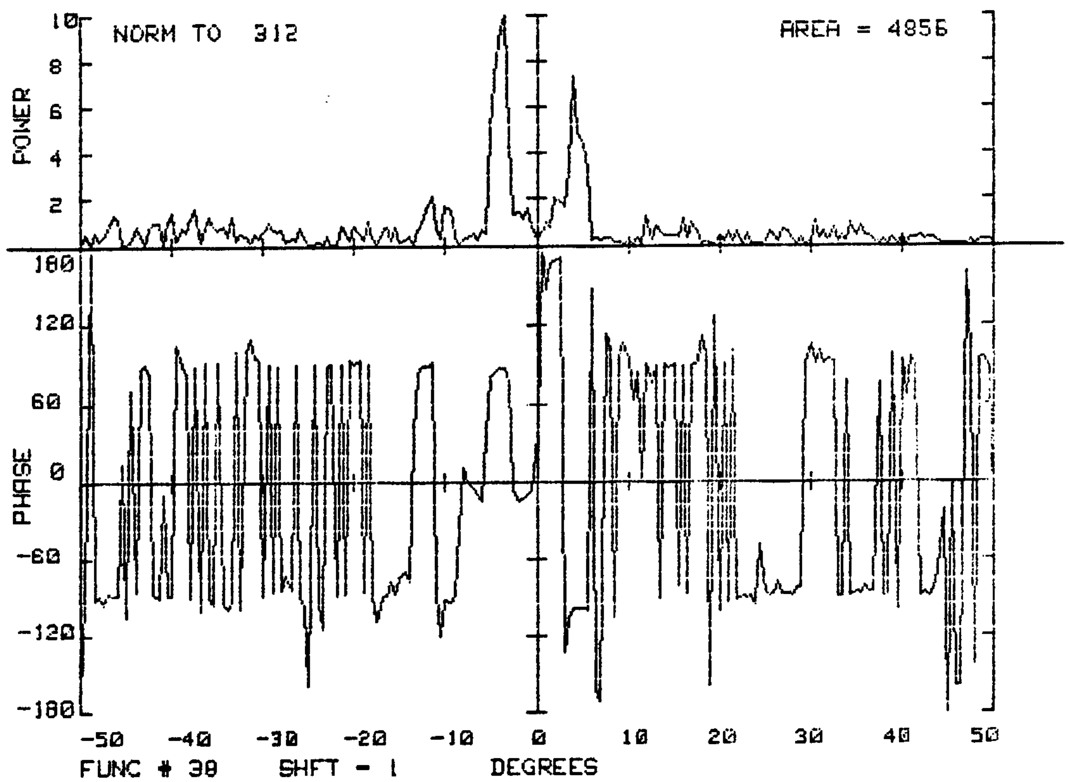


Figure 8-11. H(X,S) for Teflon Block for Height 0.19λ and S = 0.76".

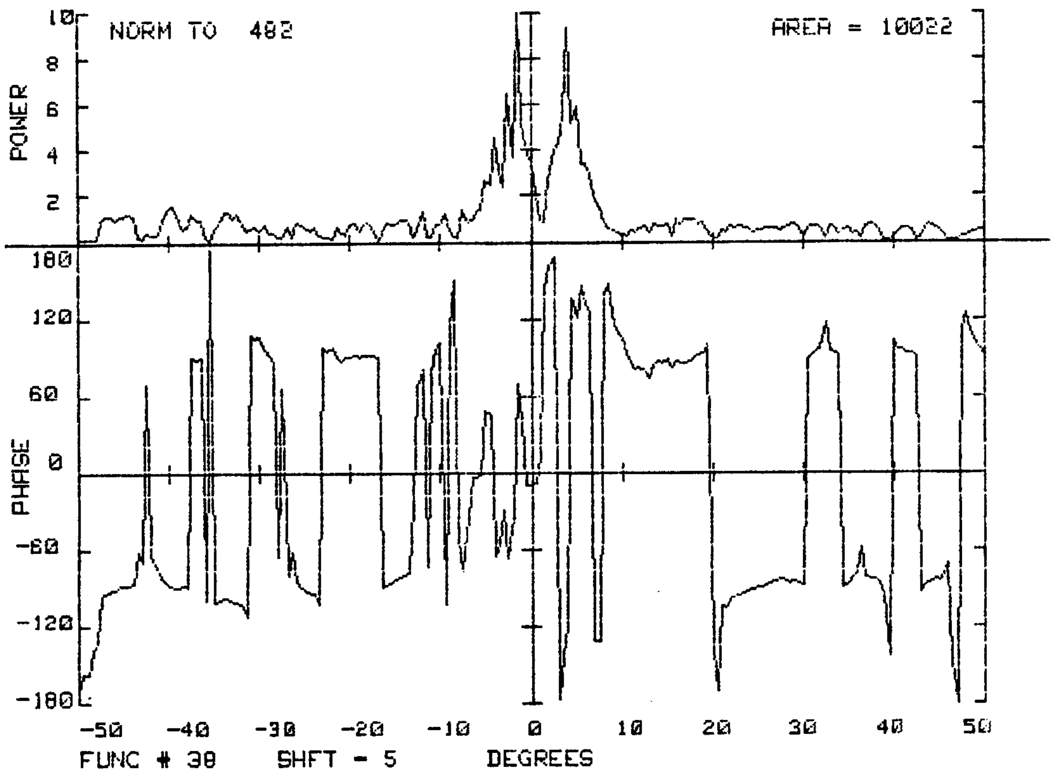


Figure 8-12. As in Figure 8-11, but S = 3.8".

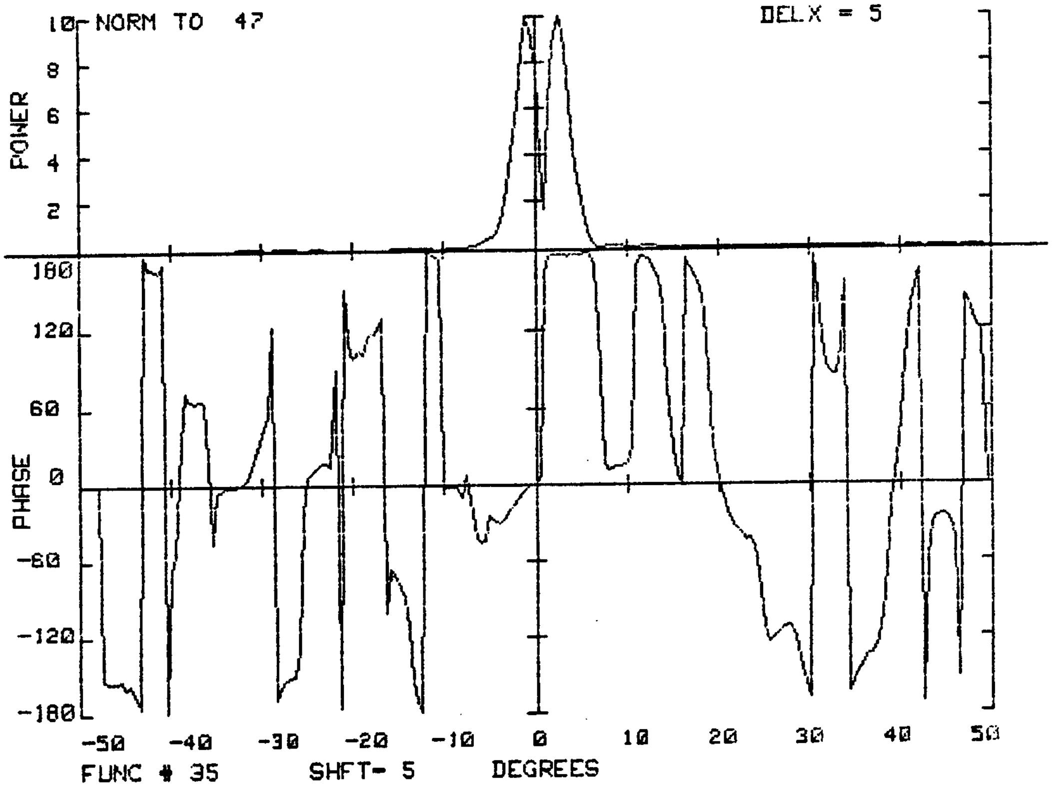


Figure 8-13. $G(X_C,S)$ Corresponding to Figure 8-9. Integration Range was 3.8".

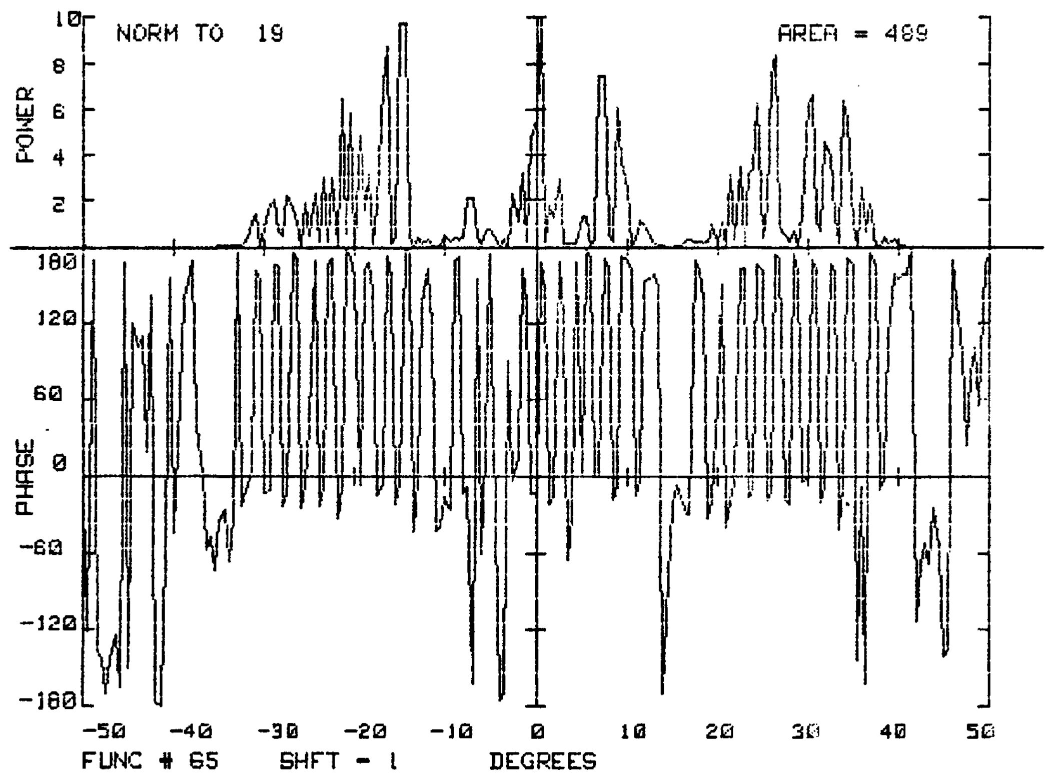


Figure 8-14. H(X,S) for Teflon Block in Corrugated Soil; S = 0.76"; h/λ = 0.06.

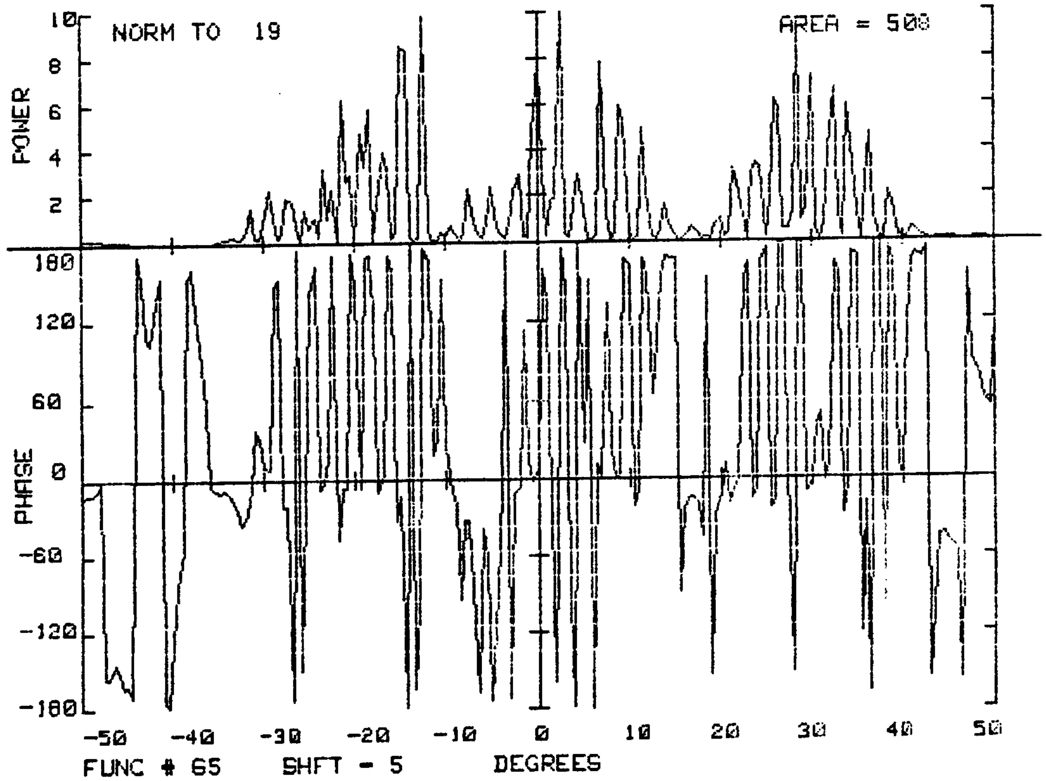


Figure 8-15. As in Figure 8-14, but S = 3.8".

When height is increased, so h/λ is 0.19, integration produces two peaks in figure 8-18; this figure should be compared with Figure 8-16.

It is clear that detection is difficult when a system operates too close to a corrugated surface. Processing with the phase switched concept helps, but it is limited. Another form such as holographic imaging may be useful.

8.2.3 Imaging by Angular Spectrum and Backward Propagation; Holography[3]

The images of Figures 5-5 through 5-8 were produced by a backward propagation algorithm based on the angular spectrum. Briefly, phase and intensity measured over an area were first Fourier transformed. The transform was multiplied by an exponential function, a propagator, which yields the transform in the soil. The propagation depends on Snell's law to describe the air-soil interface. The propagated transform was inverse transformed to yield focused images. This processing is a form of holography.

Figure 5-5 shows that the measured intensity even without processing resembles the object. By comparing Figures 5-5 and 5-7, we see that images are improved by subtracting a stored background, averaged over a region, from the measured data before processing.

Notice in Figures 5-5 through 5-8 that images are somewhat better for corrugated soil than for smooth soil. We believe that this is a property of holography, where diffusers improve images.[14,15]

Reference 3 gave additional holographic images produced by illuminating detour phase holograms with laser light. The holograms were formed at 2 GHz and scale reduced, but not in the ratio of microwave to optical wavelength; therefore, the images were small.

Further work should be done on digital reconstruction to eliminate partial scaling. This possibility is now more reasonable than it was in 1973 and 1974 when computing power was less. In fact, parallel processing seems natural. Real time optical computers are a possibility.

8.2.4 Correlation

Spatial distributions of measured data can be compared with a stored data base. In this case the distributions can be considered inputs for pattern recognition methods. The measured data or patterns, could be compared with a stored data base for mines of interest. However, the scattered fields depend on uncontrolled parameters which include soil conditions, surface roughness, mine depth, and mine orientation. Therefore image formation seems justified because images give object size independent of depth, through focusing; more study is justified. Antenna height can be measured and included in the calculations. Soil conditions could be included in the backward propagation if that variable proved significant for imaging. The notion of diffusers in holographic imaging seems potentially important for reducing the effects of rough soil surfaces; we have improved microwave holographic images by means of diffusers.

8.2.5 Other Processing Methods

We have been analyzing additional processing methods. These include Fourier spatial domain filtering, Synthetic Discriminant Functions, deconvolution, and homomorphic processing. Some preliminary evaluations are given in Table 8-1.

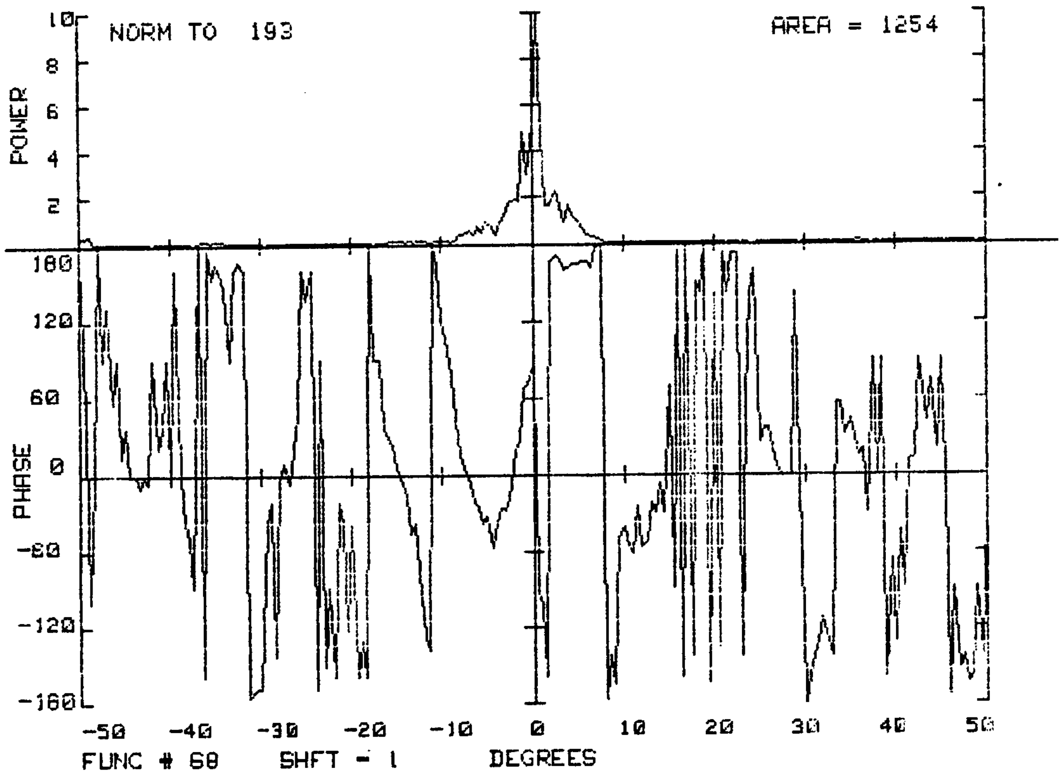


Figure 8-16. H(X,S) for Teflon Block in Corrugated Soil; $h/\lambda = 0.19$; S = 0.76".

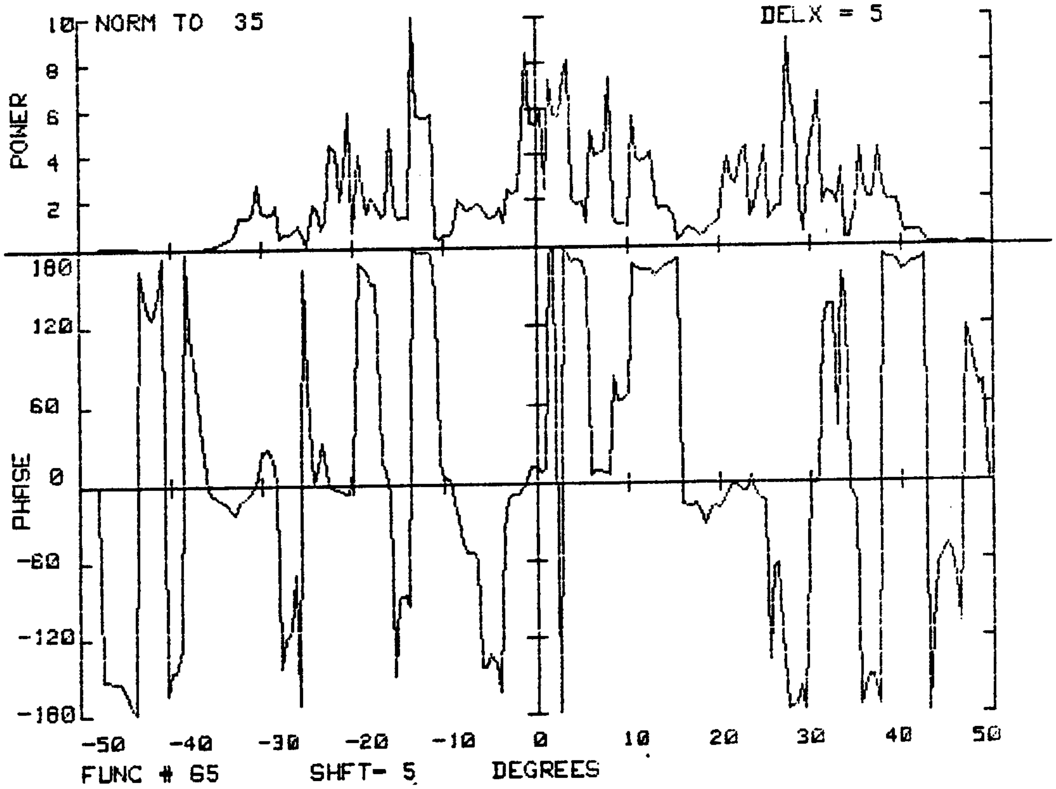


Figure 8-17. $G(X_C,S)$ for Teflon Block in Corrugated Soil; $h/\lambda = 0.06$; S = 3.8"; and 2A = 3.8". Data From Figure 8-15.

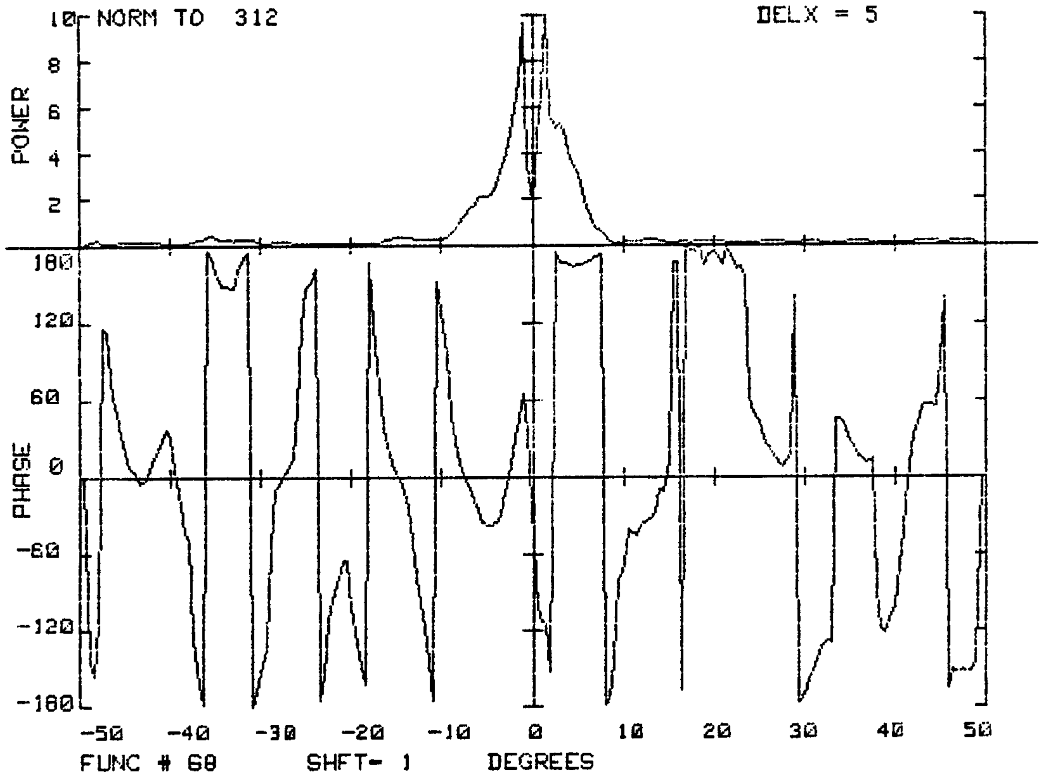


Figure 8-18. $G(X_C,S)$ for Teflon Block in Corrugated Sand; $h/\lambda = 0.19$; S = 0.76"; and 2A = 3.8". Data from Figure 8-16.

8.3 SYSTEM VIEW OF SOFTWARE

Any new electromagnetic mine detection system will probably utilize software for detection. Therefore, in designing the measurement system we considered software to assess its influence on the configuration and control of apparatus.

Software can be viewed as a system with inputs and outputs, as in Figure 8-19. We define three types of inputs; measured , system, and external. Measured inputs are quantities such as amplitude and phase of the received field. System inputs include data from radio frequency (RF) sources and from antenna position controllers and indicators. External inputs may come from the operator; examples are data on soil conditions or mine type.

A system may have two types of outputs, system and external. System outputs control antenna height, antenna position, and frequency of RF source. External outputs provide the operator indication of object detection or classification, and instructions.

The software system can be divided into a series of interrelated modules, as suggested by Figure 8-20.

The preprocessor module accepts measured data and formats it for use by the remaining modules. An examples is analog to digital and conversion. Another example is dividing the data stream into subsets.

The control module supplies the detection module with information regarding parameters such as antenna height and position.

The external inputs/output module communictes with the operator. It provides for external entry of pertinent data such as soil and target types. The output portion of the module displays measured and processed data on some device like an oscilloscope.

The control module sends signals to control system components. Some signals will select frequency, control data sampling and antenna position.

The detection module contains the algorithm that transforms the measured data. An algorithm might form an image. Another algorithm may make decisions on mine presence. In any case, the data on decision must be relayed back to the system module as well as the operator/controller.

The nature of the detection algorithm determines how data are collected and organized. Data collection formats may be divided into two broad categories; line scan and area scan. Line scan data are a one dimensional pattern values measured on an arc or straight line. Area scan data are a pattern of values measured over an area.

Some algorithms are listed in Table 8-1.* These can be applied to either line or area scans. The algorithms listed are not exclusive; for instance raw data may be deconvolved, enhanced, and then recognized by a synthetic discriminant function algorithm. Many approaches exist; however, those in Table 8-1 seem promising.

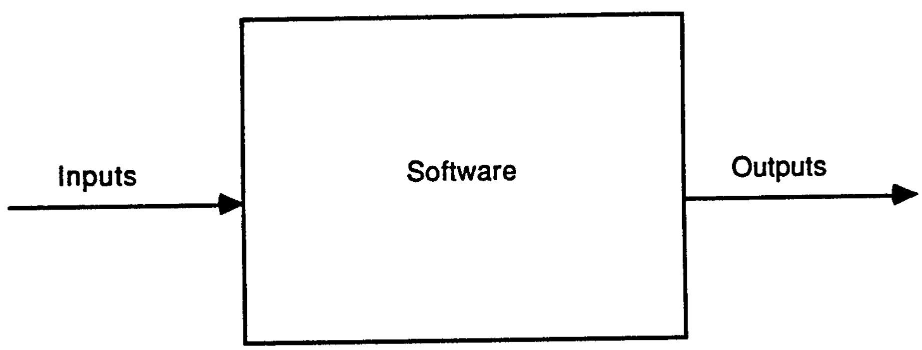


Figure 8-19. Software As A System

* Other algorithms were described in Paragraph 8.2, and images from a backward propagation algorithm were presented in Paragraph 5.3

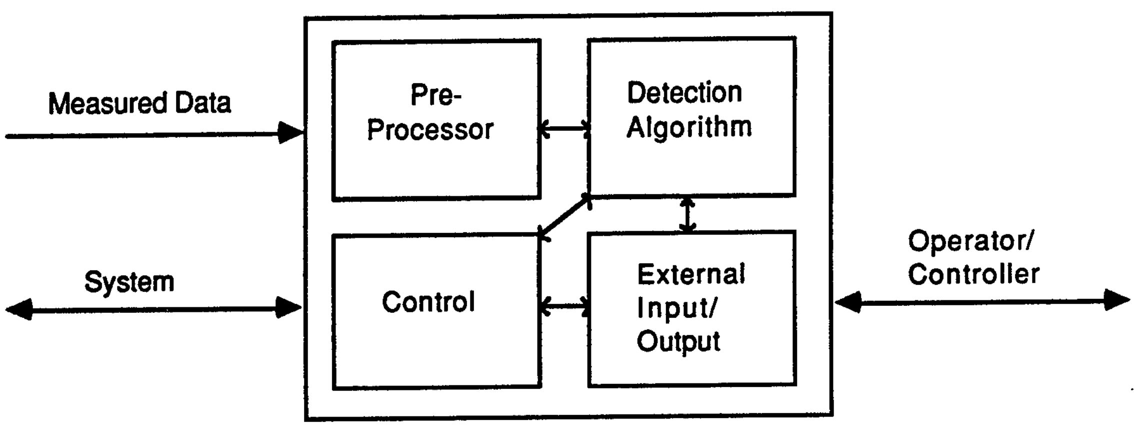


Figure 8-20. Modules Within A Software System

mine presence. In any case, the data on decision must be relayed back to the system module as well as the operator/controller.

The nature of the detection algorithm determines how data are collected and organized. Data collection formats may be divided into two broad categories; line scan and area scan. Line scan data are a one dimensional pattern values measured on an arc or straight line. Area scan data are a pattern of values measured over an area.

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* Other algorithms were described in Paragraph 8.2, and images from a backward propagation algorithm were presented in Paragraph 5.3

TABLE 8-1

SOME MINE DETECTION ALGORITHM DESCRIPTIONS

GENERAL CLASS	DESCRIPTION	EXAMPLE	COMPARISON
Spatial Domain Enhancement Operators	This class of operators is applied as preprocessors to equalize amplitude of all spatial frequency components of the measured data. Sobel processing is an example.	Differential	Pro: Complex first or second derivative operators can be applied to line or area scan data.Useful for removing background response; tend to highlight edges of anomalies. Con: Influenced by changes in antenna height or surface roughness, sensitive to data sample spacing. Not an automatic detection algorithm by itself unless slope thresholds are sole criterion, but assist an observer in detecting objects.
		Exponential	Pro: Advantages for use in balanced bridge configurations exploiting the received power increase from inhomogenous media. Con: Poor response with dipoles due to the uncertain change in received amplitude. Tends to mask finer detail. Like differentials, not a detection algorithm alone.
Fourier Domain Enhancement Opertors	Measured or preprocesed data is transferred into spatial frequency domain via discrete Fourier transforms (DFT). This permits frequency selective manipulation for the removal or enhancement of signal characteristics through the application of frequency domain masks. DFT's also provide another domain in which characteristics identification and/or pattern recognition may be utilized.	Spectral Filtering/ Masking	Pro: Excellent ability to remove background response, or enhance frequencies related to desired object size. Can eliminate responses from small objects such as metallic shrapnel and roots. Con: Because spectral filtering is done numerically and discretely, there are no computational disadvantages. However, filters must be designed
		Deconvolution	Pro: Potential for removing the influence of the measuring antenna from the data; increasing the resolution of the system. Can combine with spectral filtering in a single operation. Con: Sensitive to changes in antenna properties and antenna height. Filters must be designed.

TABLE 8-1

SOME MINE DETECTION ALGORITHM DESCRIPTIONS (cont'd)

GENERAL CLASS	DESCRIPTION	EXAMPLE	COMPARISON
Characteristic Identification	Characteristic traits such as amplitude peak and slope values, phase changes, and null widths are used to indicate mine location. These properties may also be analyzed for statistical correlation with known responses.	Amplitude/Phase Detection	Pro: Peak amplitude is reliable and adjustable detection threshold, especially for balanced bridge antennas. Con: High false alarm rate in uneven or cluttered soil. Sensitive to antenna height and object depth.
		Statistical	Pro: Has potential to resolve similar responses. Provides accurate confidence levels. Con: Requires large library of responses for accurate categoriation.Measured data depend on object depth, soil conditions, antenna height; imaging may help.
Pattern Recognition	Preprocessed data is Fourier transformed and filtered with a specialized filter, and is transformed back to spatial domain. The resulting correlation plane metrics are geometrically analyzed to determine location, confidence, and type of object detected.	Synthetic Discriminant Function (SDF)	Pro: Has high potential for identifying geometrical objects buried in noisy signals, and discriminating between mines and other objects. Con: Requires resolution in excess of current hardware capability. Most effective when applied to area scan data due to reliance on correlation plane metrics. Measured data depend on object depth, soil conditins, antenna height; imaging may help.

PART II

DESIGNS FOR THE MEASUREMENT SYSTEM

This part of the report describes two alternative designs for the measurement system.

9.0 DESIGNS

This section describes two alternative designs for the measurement system. One system would operate in the frequency band 0.0003 to 3.0 GHz; the other from 0.045 to 20 GHz. The lower frequency system would be used to evaluate components, like antennas, and to evaluate detection algorithms. Parameters include frequency and antenna height. Data would be obtained about the object, scattering by smooth and rough soil surfaces, and propagation through soil. The higher frequency system would provide the same capabilities, and it would provide frequencies that may be useful but that have not been widely used for detection.. Higher frequencies may be useful for imaging or radar methods. Costs are greater for the higher frequency system.

The basis for the designs has been described in Part I. Some material is collected in this section for unity, but Part I should be consulted for some background on the choices.

Section 9.1 describes the electronic equipment, such as source, receiver, and computer for the lower frequency system. It also describes some computer peripherals. Catalog costs are presented.

Sectin 9.2 describes the electronic equipment and peripherals for the higher frequency system, and it lists catalog costs.

9.1 System For 0.0003 to 3.0 GHz

9.1.1 Electronic Equipment and Computer Peripherals

Figure 9-1a shows block diagram of the system. It includes the following major electronic components and peripheral equipment.

- *Network Analyzer: Hewlett-Packard 8753.* This analyzer operates at frequencies between 0.0003 to 3.0 GHz. It contains a synthesized source. It provides digital output. Phase accuracy is ±0.5°; intensity accuracy is ±0.05 dB* . It has time domain capability for synthesizing pulses, with range resolution of 6 cm in air for 2.5 GHz bandwidth.

- *Test Set: Hewlett-Packard 85046A.* This instrument provides coupling for either reflection or transmission measurements.

- *Computer System: Hewlett-Packard 98580A.* This computer can control frequencies and an antenna positioner. It provides storage on floppy disks. It has enough memory to evaluate Fourier transforms over an array of 126 by 126 complex data values. Keyboard and CRT display are included with the system.

- *Disk Drive: Hewlett-Packard 9153B.* This drive provides for storage on floppy disks.

- *Printer: Hewlett-Packard 2225A.* The printer provides hard copies of measured data or analytical results.

An optional digitizing oscilloscope, Hewlett-Packard 54120T, can be included for evaluating returns from pulsed sources that are short in time and not synthesized. Pulsed sources are not included because they are specialized. Such sources would probably be supplied by a contractor or laboratory as an idea for evaluation; however, a means for independent performance evaluation seems desireable.

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* This accuracy is for the network analyzer; it excludes mismatch, connector repeatability, dynamic range, and frequency range. However, error correction software is available.

9.1.2 Antennas For The Lower Frequency System

The following antennas are included in the design. Some are conventional, for measurements; others are potentially useful for detectors.

- *Dipoles.* A set of dipoles would be necessary because of their limited bandwidths. Dipoles should be provided for frequencies fo 0.3, 0.5, 0.7, 0.9 and 1.1 GHz. Each antenna would have a removable reflector, which reduces reflections from supports; the dipole may influence reflections, so evaluation is necessary.

- *Horns.* Horn antennas would be included for the bands 0.8 GHz to 1.6 GHz and 1.5 to 3 GHz. These would be linearly polarized.

- *Log Periodic.* A log periodic antenna would be included. A Yagi-Uda array would be included for the band 0.5 to 1.2 GHz.

- *Stacked Dipoles.* Sets of two or three independent dipoles could be assembled from the dipoles described above. These antennas would be used to develop the idea of stacked antennas, shown in Figure 6-1(c).

- *Three Element Antennas.* These antennas consist of three, parallel, side-by-side dipoles, each in a reflector. The outer pair radiate out-of-phase; the inner antenna receives. Three antennas are suggested for frequencies, 0.5, 0.7, and 0.9 GHz.

The three element antennas require hybrid junctions or power splitters. We have utilized hybrid junctions, but they are rather delicate. Power splitters seem more rugged; a Hewlett-Packard 11850C is recommended.

The system will be designed to accommodate many kinds of antennas or arrays of antennas, operating in the band 0.0003 to 3.0 GHz.

9.1.3 Antenna Positioners

Two kinds of antenna positioners are suggested, as follows.

- *Turntable: Daedal 21200H.* This turntable has a single axis. A single scan generates data over an arc. To scan an area, a cart or boom is necessary in addition to the turntable. It weighs 30 lbs and has a 12 inch diameter circular plate on a 12 inch wide square base. It can support 200 lbs. It requires a Daedal controller, model 2100-1P-488-RKM. The turntable can be moved continuously or in steps; the computer (HP 98580A) can control either motion.

- *Rectangular Positioner.* This positioner would translate an antenna over a plane to measure scattered fields or to probe antenna nearfields. We have been using devices fabricated in our laboratory. In one, the antenna is supported by a metal plate that slides on two pairs of orthogonal rods. The plate is moved by chains and sprockets that are driven by electrical motors. Servo motors gives position in rectangular components.

The rectangular positioner can be supported on an axis that permits tilting it to vary incidence angle. The same positioner can be positioned to probe antenna nearfields as suggested in Figure 6-9.

This positioner must be rugged, and it should be strong enough to support an antenna array.

9.1.4 Software

Software for the HP 98580A would be provided, including the operating system, loaders, editors, compilers/interpreters, etc., supplied by Hewlett-Packard. System control and data analysis software would be developed.

System control and data analysis software will be developed. A compiled language such as PASCAL will be used.

The system control software will provide outputs to operate system components. It would select frequencies, sample phase or amplitude or both, switch the antenna arrays if used, direct antenna position and control sampling rates. It also would control test bed movement using stepping motors. All system control parameters would be selected by the operator and input into the system using display prompts and keyboard inputs.

Data analysis software manipulates measured information. Display prompts would be provided for selecting data handling options. Options would provide for data buffering and storage, plus permanent storage on disks. Type of display and format of data may be selected, as well as the medium, CRT or printer. Formats would be automatically scaled to correspond to data being measured. Some data enhancement algorithms, such as Sobel and Fourier domain processing would be included.

The data analysis software would be designed to accomodate future algorithms that may be developed at a number of laboratories. A program module would be reserved for future code; of course, the code must be written in a compatible language. A link to this module would pass pertinent data values and queuing information; it would be activated by an input option. Values of amplitude, phase, frequency, position, time, etc., would be available to the module.

9.1.5 Costs

Catalog costs are given in Table 9-1 for the commercially available equipment.

TABLE 9-1

CATALOG COSTS OF COMMERICAL EQUIPMENT

Description	Model No.	Cost
Network Analyzer	HP 8753A, with time domain and warranty	$32,000
Test Set	HP 85046A, with warranty	9,000
Computer	HP 98580A	4,000
Disk Drive	HP 9153B	1,800
Printer	HP 2225A	400
Power Splitter	HP 11850C	900
Turntable	Daedal 21200H	2,400
Controller	Daedal 2100-1P-488-RKM	4,800
	Total	$ 55,300

The optional oscilloscope's catalog cost is $28,000.

9.2 System For 0.045 to 20 GHz

9.2.1 Electronic Equipment and Computer Peripherals

Figure 9-1b shows a block diagram of the system. It includes the following major electronic components and peripheral equipment.

- *Network Analyzer: Hewlett-packard 8510E.* Operating frequencies are from 0.045 GHz to 20 Ghz. It provides digital output. Phase accuracy is ±0.5°; intensity accuracy ±0.5 dB* . It has time domain capability for synthesizing pulses, other components such as antennas may limit range resolution.

- *Synthesized Source: Hewlett-Packard 8341B.* This source operates from 0.01 to 20 Ghz. Frequency accuracy is 10^{-6} Mhz at 1 Ghz. Table 1-1 lists other performance parametrs

- *Test Set: Hewlett-Packard 8514B.* This instrument provides for power division.

- *Computer System: Hewlett-Packard 98580A.* This computer can control frequencies and an antenna positioner. It provides storage on floppy disks. It has enough memory to evaluate Fourier transforms over an array of 126 by 126 complex data values. Keyboard and CRT display are included with the system.

- *Disk Drive: Hewlett-Packard 9153B.* This drive provides for storage on floppy disks.

- *Printer: Hewlett-Packard 2225A.* The printer provides hard copies of measured data or analytical results.

An optional sampling oscilloscope, Hewlett-Packard 54120T, can be included for evaluating pulsed systems. Pulse sources are not included in the measurement system because they are specialized. The oscilloscope would provide a means for evaluating systems that utilize pulsed sources.

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* This accuracy is for the network analyzer; it excludes mismatch, connector repeatability, dynamic range, and frequency error. Error correction software is available.

9.2.2 Antennas for the Higher Frequency System

The system would include the antennas described in subparagraph 9.1.2. It would also include the following additional antennas.

- *Horns.* Horns for the band 3 to 20 Ghz would be included. Watkins-Johnson manufactures ridged waveguide horns that operate in the band 2 to 18 GHz. They provide linear or circular polarizations, which can be rapidly selected by electrical switching.
- *Log Periodic.* Log-periodic antennas would be provided for the approximate band 3 to 6 GHz and 6 to 12 Ghz.
- *Three Element Antennas.* Three element dipole arrays would be provided for the band 3 to 6 Ghz. For higher frequencies, horn arrays could be used.
- *Reflector.* A focused reflector antenna would be provided for the band 2 to 6 GHz.

9.2.3 Positioners

Positioners were described in Section 9.1.3. Mechanical tolerances would be made slightly tighter for the shorter wavelengths of the higher frequency system.

9.2.4 Software

Refer to Subsection 9.1.4.

9.2.5 Costs

Catalog costs are listed in Table 9-2 for commercially available equipment.

Table 9-2

CATALOG COST OF COMMERCIAL EQUIPMENT

Description	Model No.	Cost
Network Analyzer	HP 8510E, with time domain and warranty	$91,000
Synthesized Source	HP 8341B	17,000
Test Set	HP 8514B	included with HP 8510E
Computer	HP 98580A	4,000
Disk Drive	HP 9153B	1,800
Printer	HP 2225A	400
Power Splitter	HP 11850C,	900
Turntable	Daedal 21200H	2,400
Controller	Daedal 2100-1P-488-RKM	4,800
	Total	$ 122,300

The optional oscilloscope's catalog cost is $28,000.

9.3 System Mobility

Mine detection and identification probably requires scanning an antenna over an area. Two dimensional data may reveal mine shape better than a single scan. An area search can be implemented in four ways, as follows.

- The antenna can be supported by a boom which is on a turntable as in Figure 5-9(a), and the turntable is placed on a cart as in Figure 5-9(b). With this arrangement, the antenna scans a circular arc, and the cart is moved to scan additional arcs. The arcs are approximately parallel; for large (90 inch) radius, and small 6 inch displacements; the arcs intersect at ±90° rotation, but they are nearly parallel for angles less than 50°. This approach generates two variables, cart position and turntable angle. Stepper motors serve for both functions.

- The antenna can be supported on a turntable and the boom length can be extended. This approach generates parallel arcs. The turntable should be on a cart so the equipment can be conveniently moved to scan a considerable area. This approach generates three variables. One is for turntable angle. A second for boom length. A third for cart position. Stepper motors can be used for all three functions.

- The antenna can be supported on a linear translation carriage, which is on a cart. The translation direction is orthogonal to the cart motion. This arrangement generates two independent variables, cart position and lateral antenna position. Stepper motors would be appropriate.

- A carriage with two orthogonal linear displacements can be placed on a cart. Coordinates are two orthogonal positioners over a region of fixed size. To scan a larger area, the cart is moved. Three position sensors are needed.

The simplest approach is a fixed length boom, a turntable, and a cart. This approach is recommended as a minimum.

For analysis of algorithms, a translation mechanism with two orthogonal displacements and a cart may be more suitable than a turntable. This system would give data in rectangular coordinates, which are directly suitable for Fourier processing without interplolation, as would be the case for polar coordinates. The two dimensional positioner would also be useful for antenna nearfield measurement.

9.4 Growth

The preceding parts of this section described system designs, including radio frequency equipment, a computer, antenna scanners, and a moveable platform. The system seems adequate for measurements that will evaluate a wide range of mine detection ideas. The speed of the measurement system is adequate because the measurements will be done in controlled environment at a controlled rate. The system will utilize monostatic or simple bistatic arrangements to acquire scattering data that describe mines and that can be processed by detection algorithms. The system will evaluate components such as antennas and modulation methods. Any extensive processing of measured data, say to evaluate identification algorithms, can be done when measurements are not being done, even if the computer must run for a long time.

Although the system design is a reasonable compromise of cost, accuracy, and versatility, some emerging technologies can accelerate it and increase the kind of algorithms it can evaluate.

A faster system is desireable for the following reasons.

- *Efficiency.* More measurements can be made in a given time or a given set of measurements can be made in less time. Costs can be lowered. The chance of interruptions by weather for outdoor measurements will be reduced; for example, if rain occured during a set of mesurements, soil conditions would differ before and after the rain. Although moisture is am important variable, data sets should be consistent and comparable.

- *Amount of Data.* A large number of measurements will be necessary to characterize diverse mines in diverse environments. The minimum number is unknown, but the technical plan in Section 10 shows that many permutations of parameters are necessary to evaluate current ideas.

- *Developing and Applying New Processing Techniques.* Relatively new processing techniques, such as parallel processing and neural networks, may be necessary in new mine detectors to identify diverse mines in diverse and adverse environments. Adaptive methods may be necessary to recognize mines of unusual configurations.

- *Learning.* Direct interaction between experiment and analysis would help in establishing, modifying, and improving ideas for mine detection. Computer speeds, sizes, and capacities can be estimated.

The speed of a measurement system (and a mine detector) is limited by the times needed for measurement and for processing.

9.4.1 Measurement Speed; Parallel Data Acquisition

Mechanical motion of an antenna on a turntable restricts the rate of data acquisition. Measurement speed can be increased by acquiring data with a parallel network or antenna array as in Figure 9-2. Mechanical switches can be used in an experimental system, but electronic switches can scan an array in milliseconds. However the network analyzer's response time limits speed. Frequencies can be multiplexed to obtain data over a band. Nearly real time operation can be achieved by removing a switch and utilizing a receiver and processor at each antenna, as suggested in Figure 9-3.

The arrangment in Figure 9-2 can be generalized in several ways. A network analyzer might be imagined at each antenna, but such an arrangement would be expensive and suffer from mutual coupling. Figure 903 shows a more practical arrangement that utilizes a phase lock receiver and a transmitter with very fast monolithic microwave integrated circuit switches. Existing technology permits a phase and intensity measurement in about one nanosecond.

The arrangement in Figure 9-3 could be extended by utilizing two or more sources, to simplify and accelerate frequency changes; of course, antenna bandwidth must be considered.

Processing would follow digitization.

9.4.2 Processing Speed

Processing speed is limited by analog to digital conversion devices and the 98580A computer, which is a serial processor. Serial processors perform computations in sequential steps, and access to storage or output may interupt computation. The limitation of processing speed can be overcome by faster analog to digital conversion devices and by faster processors.

Microprocessors designed for digital signal processing should be evaluated. These devices are designed for applications involving rapid measurements, computation, and outputs. Their hardware can compute in nanoseconds what average personal computers do in milliseconds. Antenna arrays might use a transmitter, receiver and processor at each element, but system designs must consider coherence and the physical basis for processing, before such systems architectures are tried.

Parallel processors are a relatively new class of fast computers which are being rapidly developed by several universities and firms. Digital parallel processors have networks of processing elements that operate simultaneously, rather than sequentially. Certain elements perform certain computations. Data may flow on a number of paths rather than on one as in serial computers.

Some parallel computers have an architecture known as a hypercube. Examples are as follows.

- *T-Series of Floating Point Systems.* This machine's estimated operation rate is 7 million floating point operations per second (megaflops)

- *Butterfly of Bolt, Beranek, and Newmam.* This machine has an estimated 1 megaflop operation rate.

- *Connection Machine of Thinking Machines Corporation.* This machine currently uses one bit processors, but it is being modified to more capable processors.

- *WARP Computer.* This machine is being developed by Carnegie-Mellon University and the General Electric Company. It's operation rate is 100 megaflops. It utilizes a systolic array of 10 or more processors.* It utilizes a high-level language computer and a Sun 3 workstation running in ATT's UNIX system. Parallelism is achieved by partitioning the algorithm among processors.

Parallel processing may in the future be implemented by neural networks. Although still early, these networks have some promise for prefiltering large amounts of data. Recently, enthusiasm has increased, especially among computer specialists. Some solid achievements were made about 20 years ago by Widrow in work on adaptive filtering.[16] Adaptive methods may be useful in new mine detectors to identify a variety of mines in diverse conditions by organizing or modifying connections in antenna arrays; moreover, frequencies may be adapted for soil moisture and roughness and for object size.

Parallel processing can be done in real time by spatial non-coherent reconstruction of microwave holograms.[17] The feasibility of this method has been demonstrated in laboratory tests of a fiber optical system. Because of the

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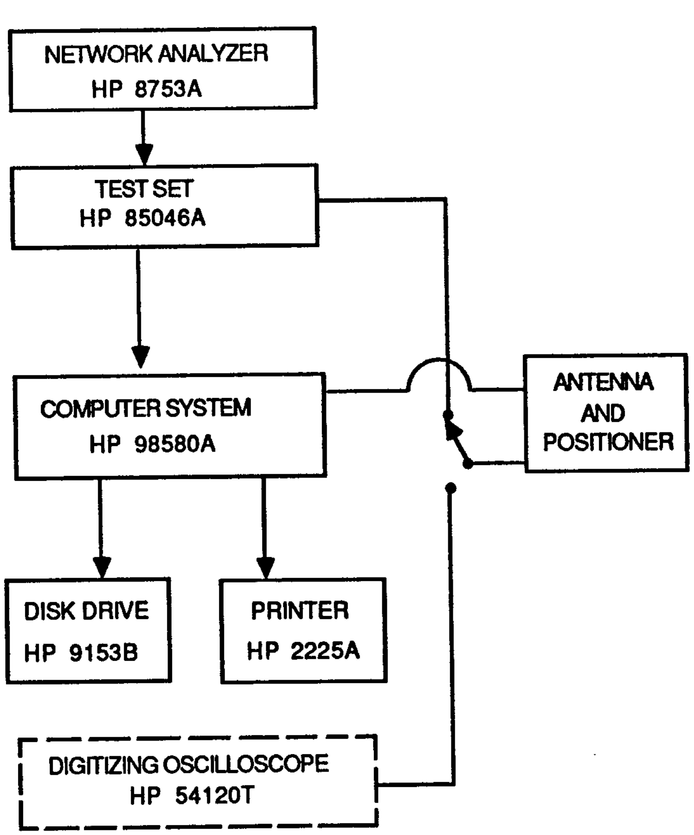
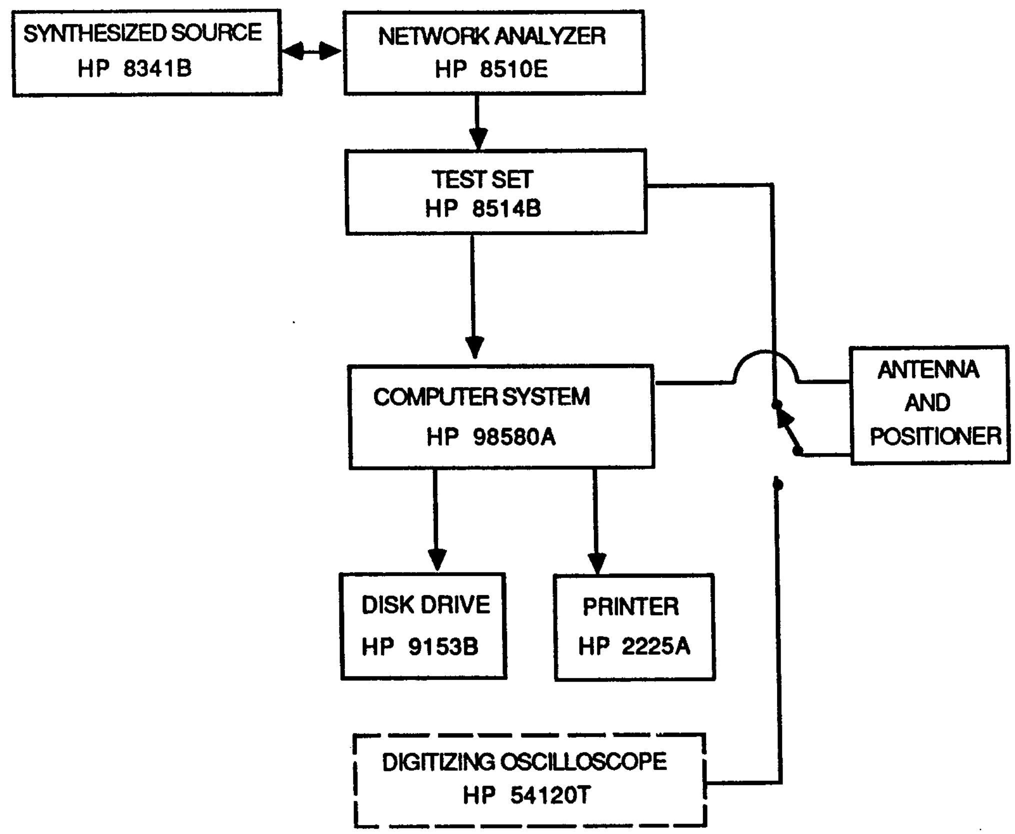
* In a systolic array architecture data goes into the first processor, which performs an operation, then passes the data to the next processor.



(a) System for 0.0003 to 3.0 GHz



(b) System for .045 to 20.0 GHz

Figure 9-1. Block Diagram of Two Alternate Measurement System. The Sampling Oscilloscope Is An Option.

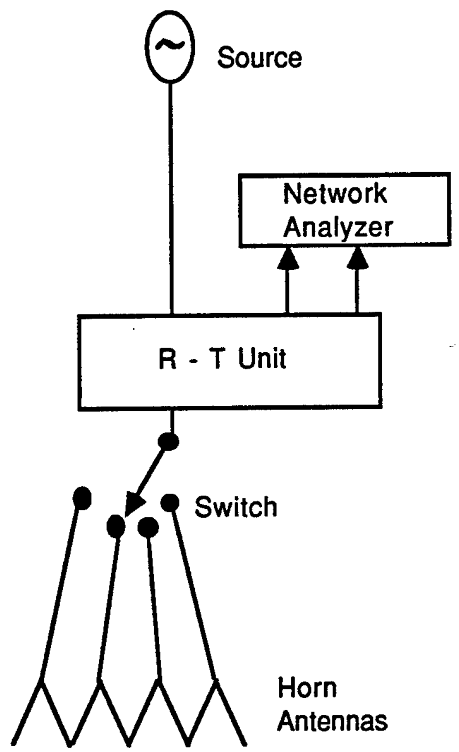


Figure 9-2. Experimental Arrangement With Four Antenna Array For Time Sequential, Parallel Data Acquisition.

PART III

TECHNICAL PLAN FOR ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS

This section presents a plan for analytical and experimental investigations. Experiments would be done with the measurement system described in Section 9; specific experiments are suggested for a variety of conditions. The analytical investigations include interpretation of experiments to determine how specific variables influence scattering; in addition, some processing techniques for identifiction are described.

10.0 TECHNICAL PLAN

10.1 Laboratory Measurement

Measurements should be made in a mine lane for a variety of buried objects; measurements also should be made with the objects absent.* The purpose is to determine the spatial distribution of phase and intensity in measured fields. The field distributions can be used in many ways. Studying them gives intution on scattering for diverse conditions; frequencies that best detect certain mines can be determined. Comparison with computed results can evaluate scattering theories, which can be more general and less expensive than measurements. Processing can evaluate detection and identification methods. In addition, subsystems, such as antennas, can be evaluated by comparing how distinct subsystems influence measured distributions or processed data.

Several experimental arrangements should be investigated. Monostatic arrangements as in Figure 6-1 should be used initially because they are simpler than bistatic; they are useful for evaluating antennas. After monostatic data have been obtained, field distributions could be probed with the bistatic apparatus in

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* Differences between the fields with and without object give the scattered fields, which are useful for physical understanding. Differencing deletes reflections from the air-soil interface and from probe supports. Differences are approximate because burying an object disturbes the soil. Note that practical mine detectors measure the total field which includes those from objects and the interface.

Figure 6-2; however, object scattering is masked by direct coupling between antennas and by reflections from the soil surface and probe supports. Although data can be corrected by subtracting data taken with the object absent, multiple scattering makes the correction approximate. Another approach to probing is to utilize a ground plane with a probe translated by a sliding section as in Figure 10-1. This arrangement is a modification of a setup that includes a rotating circular section in a ground plane.[18]

More general antenna arrangements such as arrays should be investigated because they can accelerate data acquisition. Figure 9-2 shows an array of four independent antennas which receive and transmit sequentially. Note this array is not a coherent, phased array. The antennas radiate independently. The switch in Figure 9-2 can be mechanical, but electronic switches are faster. Truly parallel acquisition can be achieved by an array of antennas and a receiver for each antenna.

Soil parameters would be measured with transmission line methods for samples; reflection methods would also be used.

10.1.1 Discussion of Variables: Components, Techniques, and Conditions for Investigation

Many components and techniques must be investigated for a range of conditions. This section describes several key items.

<u>Antennas</u> - Antennas smooth the measured field, scatter, and have limited bandwidths. Measurements should be made with several kinds of antennas, as follows.

- *Dipole.* These antennas are simple and relatively compact, but they have narrow bandwidths.

- *Dipole with Reflector.* A reflector reduces reflections from supports.

- *Stacked Dipoles.* Two or three dipoles can be stacked as in Figure 6-1(c), with a separate source for each antenna. The purpose is to obtain multiple frequency data in one scan and to overcome height dependence.

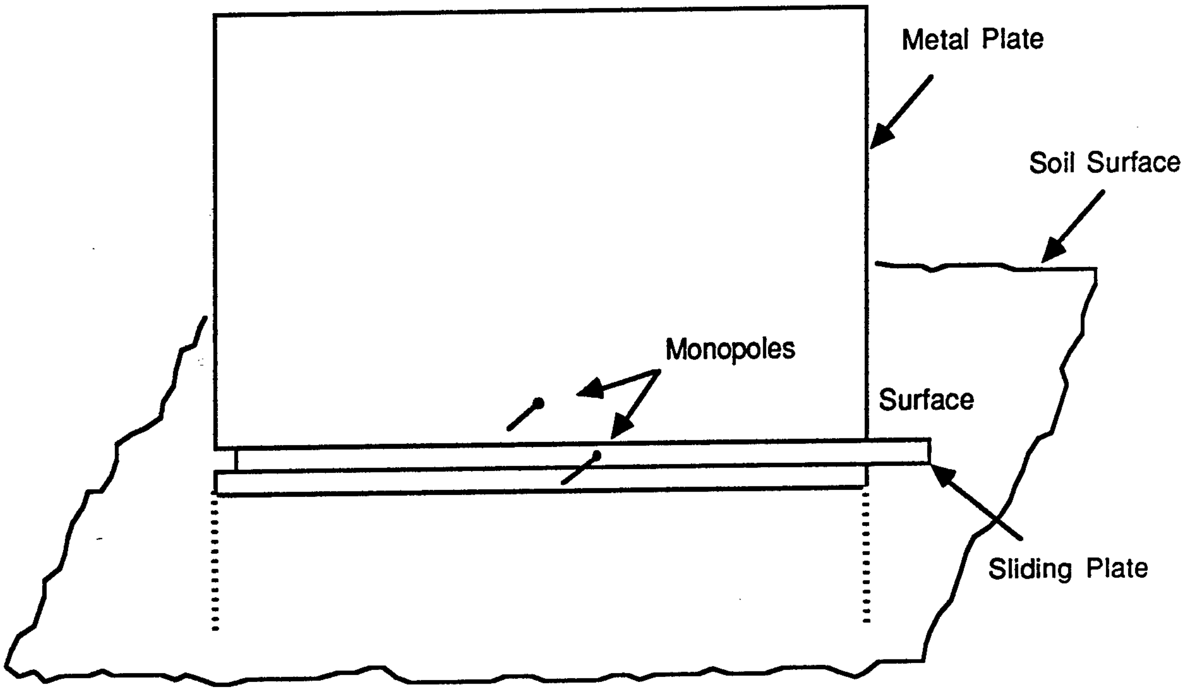

Figure 10-1. Mechanism For Probing Near The Soil Surface With A Probe In A Ground Plane.

- *Yagi-Uda.* These broadband antennas would permit frequency multiplexing during a scan.

- *Three Element Arrays.* Two out-of-phase transmitting antennas are separated by a receiving antenna. See Figure 6-5.

- *Four Horn Array.* This arrangement, shown in Figure 9-2, is a prototype for a system that gathers data in parallel. Parallel acquisition would require a receiver for each antenna, but experiments can be done with a single, switched receiver.

- *Paraboloidal Reflector.* Reflectors permit focusing. Tilting the antenna scans the beam.

Antenna Scanning. The antenna would be translated in a horizontal plane, over circular or straight paths to determine lateral extent of the measured field.

- *Antenna Height.* Height influences the magnitude of the measured field through the effects of diffraction and through wavefront expansion.

- *Polarization.* The electric field can be either aligned with or orthogonal to the scan path.

- *Antenna Orientation.* The simpler antennas, such as dipoles, probably should be horizontal; horns and reflectors can be pointed for non-normal incidence.

- *Soil Surface.* Measurements would be made first with smooth soil, which is a reproducible condition. Measurements also would be made with corrugated soil to evaluate diffusing effects of roughness. Later in this section, outdoor measurements over natural terrain are suggested. Moisture content would be determined from samples.

- *Frequency.* Wave frequency is significant in relation to scattering from the buried objects and soil surface. Frequency changes also influence antenna performance.

- *Buried Objects.* Several objects should be utilized to obtain some generality. Materials must be selected. Teflon has dielectric constant 2.1, well below that of most soils. Nylon has dielectric constant 2.9, near that of dry soil. Shape may be significant; both square and circular shapes should be included. Size is significant; at least two sizes are needed. Experiments with an inert PM-60 mine are suggested.

Time Domain Measurements. Pulsed radiation has potential for mine detection. However, problems exist with resolving a mine and the soil surface and with interpreting the data. Dynamic range may be a problem. Further investigation seems justified.

10.1.2 Scope of Measurement Task

Subsection 10.1.2 described many parameters, and implied that each parameter can have many values or conditions. Therefore, the number of measurements will be large.* To understand the scope of the measurement task, consider Table 10-1 which describes the main conditions for measurements. To simplify the presentation, Table 10-1 contains abreviations, which are defined in Table 10-2. Some clarification is necessary. Antennas would be scanned on several paths to obtain data over an area; the paths may be circular or linear. The measurements with an object absent may be repeated frequently to observe effects of soil compaction after burying an object. Five objects have been chosen; they seem a realistic sample of sizes and dielectric constants.

The number of measurements will be large. To see why consider Table 10-1.

The permutations of conditions in Table 10-1 requires approximately 10,000 scans of antennas. To estimate the time required, consider that a data record can be taken in less than a minute. In contiuous operation, data taking would than require about 170 hours or 21 working days. However, the time required will be longer because equipment must be changed or adjusted. For example, dipole antennas must be changed when frequency is changed. Additional time will be taken in changing objects and the soil surface. A rough estimate is that about 100

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* The plan is an estimate of what is necessary. It does not include all possible permutations of conditions. It can be revised.

TABLE 10-1

SETS OF LABORATORY MEASUREMENTS

(Refer to Table 10-2 For Definitions of Symbols)

SET	TEST SETUP	OBJECT	SOIL SURFACE	ANTENNA TYPE	ANTENNA HEIGHT(λ)	FREQUENCY (GHZ)	ANTENNA SCAN[e]	POLARI-ZATION	OBJECT DEPTH
1	M	O,TL,NL,TC,TCS,PM	S,C	D[a]	.05,.1,.2,.4	0.3,0.5,0.8,1.2,1.6,2.0	Z	A & O	0",2",4"
2	M	O,TL,NL,TC,TCS.PM	S,C	DR[a]	.05,.1,.2,.4	0.3,0.5,0.8,1.2,1.6,2.0	Z	A & O	0",2",4"
3	M	O,TL,NL,TC,TCS,PM	S	DS	.05,.1,.2,.4	0.3,0.5,0.8	Z	A & O	0",2",4"
4	M	O,TL,NL,TC,TCS.PM	S	H	.05,.1,.2,.4	0.8,1.2,2.0,2.5	Z	A & O	0",2",4"
5	M	O,TL,NL,TC,TCS,PM	S	Y	.05,.1,.2,.4	0.3,0.5,0.8,1.2	Z	A & O	0",2",4"
6	M	O,TL,NL,TC,TCS,PM	S	4	.05,.1,.2,.4	2.5	Z	A & O	0",2",4"
7	M	O,TL,NL,TC,TCS,PM	S	P	.05,.1,.2,.4	2.5	Z	A & O	0",2",4"
8	M	O,TL,NL,TC,TCS	S	D	Varied	0.5,0.8,1.2	V	Horizontal	0",2"
9	M	O,TL,NL,TC,TCS	S	H	Varied	0.8,	V	Horizontal	0",2"
10[b]	B	O,TL,TC,TCS	S	D or DR	Trans:0.2 rec:0.1,0.2,0.4	0.5,1.2	Z	O	0",2",4"
11[c]	B	O,TL	S	M	Trans:0.2 rec:0.15,0.25	0.8	Z	O	0",2",4"
12	B	O,TL,NL,TC,TCS,PM	S,C	3[d]	.05,.1,.2,.4	0.5,0.8,1.2,1.6	Z	A & O	0",2"

a - Measurement would first be done with each antenna tuned to its operating frequency. For comparison with Set 2, measurement would be done with the antenna tuned to 0.5 GHz.
b - Experimental setup as in Figure 6-2.
c - Experimental setup as in Figure 10-1
d - See Figure 6-5
e - Several paths would be scanned

TABLE 10-2

DEFINITIONS OF ABREVIATIONS

TEST SETUP:

M	Monostatic
B	Bistatic

OBJECT:

TL	Teflon Block: 12" x 12" x 3"
NL	Nylon Block: 12" x 12" x 3"
TC	Teflon Cylinder: 12" Diameter, 3" Thick
TCS	Teflon Cylinder: 6" Diameter, 2" Thick
PM	PM60 Mine, Inert
O	No Object; Soil Only

SOIL SURFACE:

S	Smooth
C	Periodically Corrugated
N	Natural

ANTENNA TYPE:

D	Dipole
DR	Dipole with Reflector
DS	Stacked Dipoles (may be D or DR)
H	Horn
Y	Yagi-Uda Array
3	Three Dipole Array
4	Four Element Array, See Figure 9-2
M	Monopoles, see Figure 10-1
P	Paraboidal Reflector

ANTENNA SCAN:

Z	Horizontal
V	Vertical

POLARIZATION:

A	Aligned with Scan Direction
O	Orthogonal to Scan Direction

measurements can be taken per day. Thus, about 100 days seems appropriate for the measurements of Table 10-1. Notice that the table only includes laboratory measurements, not field tests, which also are justified to utilize natural terrain.

Because the number of measurements will be large, data would be digitized and recorded by a computer rather than on charts or analog tape. Computer data acquisition permits cataloging the data. Moreover, the digitized data can be examined simply for easy interpretation by forming differences for similar conditions. For example, the intensity measured during antenna scans for two antenna heights can be subtracted, and the difference can be plotted as a single curve; in addition, the maximum difference can be determined so two curves can be compressed to a single number. Differences can be formed for many scans. Of course, the simple approach of differences is no substitute for other forms of processing; it may help to discern trends in data.

10.2 Measurements In The Field

The preceding subsection described measurements in a laboratory environment. Measurements should also be made outdoors, for natural terrain, to evaluate effects on reception and processing. Of course, enough different kinds of terrain must be included. Both moist and dry soil should be utilized; in addition, rough and smooth soil should be used. Therefore, at least four soil conditions seem necessary.

Field measurements require a method for moving the measurement system. A cart like that in Figure 5-9 is a reasonable choice. Stepper motors could accurately move the cart. A portable power generator would be needed for remote sites without electricity.

Table 10-3 lists a set of conditions that seem reasonable for outdoor measurements.* Two key parameters are antenna height and soil surface. The surface must be quantitatively described, perhaps through mean height deviation and horizontal scale. An infra-red or sonic profilometer may be useful. Antenna

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* Table 10-3 is less specific than Table 10-2 because soil parameters are not yet known and because only some antennas may merit use. Four soil conditions are anticipated.

TABLE 10-3
CONDITIONS FOR OUTDOOR EXPERIMENTS

SET	TEST SETUP	OBJECT	ANTENNA TYPE	ANTENNA HEIGHT( )	FREQUENCY (GHZ)	ANTENNA SCAN	POLARI-ZATION	OBJECT DEPTH
13	M	O,TL,NL,TC,TCS	D or DR	.1,.2,.4	0.3,0.5,0.8,1.2,1.6,2.0	Z	A & O	0",2",4"
14	M	O,TL,NL,TC,TCS	DS	.1,.2,.4	0.3,0.5,0.8,1.2,	Z	A & O	0",2",4"
15	M	O,TL,NL,TC,TCS	H	.1,.2,.4	0.8,1.2,1.6,2.0,2.5	Z	A & O	0",2",4"
16	M	O,TL,NL,TC,TCS	Y	.1,.2,.4	0.3,0.5,0.8,1.2	Z	A & O	0",2",4"
17	M	O,TL,NL,TC,TCS	4	.1,.2,.4	2.5	Z	A & O	0",2",4"
18	M	O,TL,NL,TC,TCS	P	.1,.2,.4	2.5	Z	A & O	0",2",4"
19	B	O,TL,NL,TC,TCS	3	.1,.2,.4	0.5,0.8,1.2,1.6	Z	A & O	0",2",4"
20	M	O,TL	D or DR	Varied	0.3,0.5,0.8,2.0	V	Horizontal	0",2"
21	M	O,TL	H	.1,.2,.4	0.8,2.0	V	Horizontal	0",2"

height should be recorded, again by a profilometer. The measurements would provide the opportunity for testing an automatic mechanism that maintains height.

10.3 Analysis

The analysis should include the following.

- *Analysis of Measured Data.* The data should be examined visually. To obtain a rough summary, differences would be formed between pairs of curves for different conditions such as antenna heights, and the maximum difference would be stored to describe that pair. This procedure probably is more suitable for intensity than phase because intensity data seem more stable with small changes of conditions. Careful calibration is required.

- *Comparison With Scattering Theories.* Mei's and Hill's theories would be compared with experimental results. For simple analysis, predictions from Equation 5-6 would be compared with measurement, and ray tracing calcuations would be made with Equation 5-4. Of course, soil properties would be necessary. Frequency variations of reflected fields would be analyzed for resonances related to object size and wavelength in soil.

- *Gradient Techniques.* The Sobel method, described in Subsection 8.2.1, would be applied to data taken on a line and over an arc.

- *Fourier Domain Enhancement.* Spatial frequencies would be computed, and filters would be designed. This method is described in Section 8.2.5.

- *Imaging.* Image would be formed by spatial Fourier transformation of fields, backward propagation, and inverse transformation. The theory was described in Subsection 8.2.3. Statistical properties of soil roughness would be examined to develop subtraction techniques for removing the air-soil interface reflection.

- *Pattern Recognition.* Correlation methods would be applied to two kinds of data. One is measured patterns of phase and intensity, for both line and area data. The other kind is images. Parameters to be evaluated are object orientation, frequency, antenna height, object depth, and soil conditions.

The scope of the analysis is uncertain. Analytical results probably will depend on many parameters. Some analytical methods may work better for certain environments and objects but not so well for others.

Some consideration should be given to advanced methods such as neural network analysis by digital computation. Some algorithms exist for pattern recognition by spatial frequency analysis of measured data. The algorithms would require what is called training; that is establishing values of parameters that yield identification. This analysis would estimate the value of neural network methods and help determine the scope of computers needed for practical mine detectors.

Adaptive methods should also be considered. Parameters for adaptivity include wave frequency and antenna height. In addition, antenna array connections can be altered, by weighting nearfield distributions to give antenna patterns with shapes that may improve identification. Adaptive filtering of spatial frequency transforms may be possible for nearly real time detection. Spatial coherence of arrays should be studied.[17]

Two very advanced techniques might be considered, but they require research. First, millimeter wave waveguides should be studied for use in real time optical computation. Second, the potential of phase conjugate optics for holographic reconstruction should be assessed. Phase conjugation means reversing the algebraic signs of phase variations; it is done in non-linear materials. Conjugating wavefronts may remove aberrations such as those produced by rough soil.

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