Research with the Waveguide Beyond Cutoff or Separated Aperture Dielectric Anomaly Detection Scheme

Report 2497

Author: Dr. Lloyd B. Ringle
This document is the best quality available. The copy furnished to DTIC contained pages that may have the following quality problems:

- Pages smaller or larger than normal.
- Pages with background color or light colored printing.
- Pages with small type or poor printing; and or
- Pages with continuous tone material or color photographs.

Due to various output media available these conditions may or may not cause poor legibility in the microfiche or hardcopy output you receive.

☐ If this block is checked, the copy furnished to DTIC contained pages with color printing, that when reproduced in Black and White, may change detail of the original copy.
This report presents experimental results concerning the separated aperture (or waveguide beyond cutoff) buried mine detection scheme. The primary purpose of this research effort is to contribute to an engineering database to be used in a long term research program directed toward the development of a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique and to assess the general feasibility of separated aperture mine detectors. Keywords: Land Mines; Mine Detection. (PM)
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>SECTION I</th>
<th>INTRODUCTION</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fundamental Operating Principles of the Waveguide</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Beyond Cutoff Buried Mine Detection Scheme</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Historical Perspective</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Lessons Learned and Issues Raised</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Present Efforts and Future Plans</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION II</th>
<th>EXPERIMENTAL RESULTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data Collection System</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Broadband and Printed Circuit Sensor</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Experimental Procedure</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Soil and Anomaly Constitutive Parameters</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Coupling as a Function of Sensor Height</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Soil Homogeneity and Control of Sensor Height</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Ability of 790 MHz Sensor Head to Detect a Buried Nylon Block</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Sensor Response as a Function of Position</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SECTION III</th>
<th>SUMMARY</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observations</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Recommendations for Further Research</td>
<td>14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>REFERENCES</th>
<th></th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>REFERENCES</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>APPENDIX A</th>
<th>ILLUSTRATIONS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APPENDIX A ILLUSTRATIONS</td>
<td>A-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>APPENDIX B</th>
<th>COMPUTER CONTROL/DATA COLLECTION SOFTWARE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APPENDIX B COMPUTER CONTROL/DATA COLLECTION SOFTWARE</td>
<td>B-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>APPENDIX C</th>
<th>PLOTTING SOFTWARE</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>APPENDIX C PLOTTING SOFTWARE</td>
<td>C-1</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENTS

The authors would like to extend their sincere appreciation to Mr. Russ Chesley and Mr. Brian Mayberry of the Fort Belvoir Experimental Mine Lanes Facility for their valuable guidance and suggestions throughout the experimental data collection phase of this effort. We would also like to extend a special thanks to Mr. Robert Brooke for many stimulating discussions regarding the separated aperture mine detection technique. The first listed author would like to thank Dr. Tom Broach, Mr. Bob Bernard, Dr. David Heberlein, and Dr. Karl Steinbach for providing him with the opportunity to work with the Countermine Technology Division at Fort Belvoir, VA.
SECTION I. INTRODUCTION

FUNDAMENTAL OPERATING PRINCIPLES OF THE WAVEGUIDE BEYOND CUTOFF BURIED MINE DETECTION SCHEME

Figure 1 (see Appendix A) shows a simplified representation of the separated aperture or waveguide beyond cutoff mine detection scheme. As shown, the sensor is composed of a transmit and receive dipole pair separated by a metallic septum. Each dipole resides within a corner reflector. For a fixed input power, the output power measured at the receiving dipole is monitored. As the sensor head moves over the surface of the earth, the received power varies. When the sensor head is over uniform background (no mine present) very little power is received. There is a significant increase in received power when the sensor head is over a mine.

Although the separated aperture approach to mine detection is simple, it has certain, very desirable features that are not shared by other electromagnetic mine detection methods. Electromagnetic identification of buried mines requires a transmitter and receiver. Energy from the transmitter penetrates the earth surface, interacts with the buried mine, and is then coupled into the receiver for detection. Unfortunately, a rather large amount of energy can be directly coupled from transmitter to receiver or reflected from the air-soil interface and coupled into the receiver. Energy at the receiver which interacts with the mine (the signal) can be quite small in comparison with this direct and ground reflected energy (the clutter). The advantage of the separated aperture approach over other electromagnetic detection techniques is that, under proper operating conditions, the direct and ground reflected signals are substantially suppressed in comparison with the return from the buried mine. The metallic septum forms a waveguide with the earth's surface and when the septum-earth separation is small, this waveguide is below cutoff resulting in an exponential attenuation of the direct and ground reflected signals and a vastly improved signal-to-clutter ratio. In fact, according to one source, the waveguide beyond cutoff sensor exhibited the best signal-to-clutter ratio of any technique ever attempted.

HISTORICAL PERSPECTIVE

As discussed in the report, MERADCOM Mine Detection Program: 1960-1980:

"The waveguide beyond cutoff concept was discovered in the 50's and implemented in a portable (hand held) mine detector, the PRS-6, which was never type classified. Experimental data collected under controlled conditions exhibited the best signal-to-clutter ratio of any technique ever attempted, and tests against the PRS-4 revealed it to be superior in both detection and false-alarm rejection. Its major drawback was its height sensitivity which produced a false alarm signal when the antenna reached a height of one-half wavelength. The PRS-4 and PRS-7, which had lower detection capability, merely ceased to detect without alarm and had, therefore, greater user acceptance."
Research leading to a vehicular-mounted road mine detection system based on the separated aperture approach was conducted from the early 1970s to April 1982. The development effort was undertaken by the Belvoir RD&E Center with technical support from the National Bureau of Standards (NBS) (now the National Institute of Standards and Technology (NIST)) and the Cubic Corporation. According to Report 2412, Vehicle-Mounted Road Mine Detector System (VMRMDS), AN/VRS-5:

"Concentrated investigative efforts were conducted by the Bureau of Standards in the antenna design and frequency determinations. The Cubic Corporation was contracted to proceed in the tasks of electronic signal transposing for field use and mechanical development for vehicle-mounted field use." 2

A Vehicle-Mounted Road Mine Detection System (VMRMDS), AN/VRS-5, shown in Figure 2 (see Appendix A), was eventually constructed and subjected to Operational Testing (OTII) by the Armor and Engineer Board at Fort Knox, KY, between January and April 1982. Many system deficiencies were noted during this test, the most serious of which was the extremely poor mine detection rates of mines buried in high-moisture content soils and mines subjected to vehicle wheel or tread compaction. Again, according to Report 2412:

"During the same time period (between January and April 1982), TRADOC determined that there was no longer a requirement for a vehicle-mounted mine detector which could be used only on roads or other flat terrain. By letter US Army Engineer School (TRADOC proponent), ATZA-CDM, 9 April 1984, withdrew the requirement for the system causing DARCOM (now AMC) to direct termination of the program." 2

LESSONS LEARNED AND ISSUES RAISED

Although the VMRMDS previously discussed was never accepted by the Army, the separated aperture approach to mine detection, for reasons outlined above, is nevertheless considered by knowledgeable individuals at the Belvoir RD&E Center to be one of the best mine-detection schemes ever developed both in terms of detection reliability and false-alarm rejection. The technique is, however, limited to relatively level, sparsely vegetated terrain since the septum earth separation must be small to achieve the waveguide below cutoff effect discussed above.

Much was learned from past theoretical and experimental research efforts with the separated aperture mine detection technique. However, the eventual failure of the AN/VRS-5 exposed several important limitations that must be addressed before another full scale development program can be pursued. Some of the most important issues which must be resolved are as follows:

1 A mine buried in soil with high moisture content seems to be extremely difficult to detect and, as expected, the situation is exacerbated as the mine is buried deeper. Past research efforts were conducted with two types of dipoles, a narrow band printed circuit dipole (PC dipole) used by the Cubic Corporation, and a relatively broadband brass dipole used by NBS. It was observed that the PC dipoles give good detection performance with mines buried in homogeneous, relatively dry soil. However, the response in moist or wet soil is known to degrade. Some evidence exists supporting the notion that the broadband dipole would perform much better under these conditions. Preliminary NBS research also
indicated that some frequencies penetrate moist soils much more efficiently than do others so that a "window of opportunity" may exist which can be used to enhance detection under wet conditions. These rumors and conjectures must be carefully investigated. Even if it turns out that the separated aperture approach simply does not work well in moist soil, this will still be important information regarding the generation of realistic specifications for a prototype vehicular and/or hand-held mine detector.

2 The operating bandwidth and frequency sampling interval must be optimized for best detection performance. The optimum choice for one set of conditions (e.g., dry soil) might not at all be optimum under other conditions (e.g., wet soil). Expansion at the lower end of the bandwidth could improve the performance in wet and heterogeneous soils. (Because of skin effect, low frequency energy generally penetrates lossy soil more effectively than does high frequency energy.3) NBS research indicated a greater confidence in 10 MHz interval bandwidth readings than with 20 MHz. Any "new start" program should carefully review the bandwidth/sampling interval issue.

Other deficiencies were outlined in Report 2412.2 Throughout the history of the VMRMDS development, there was only one known correlation of simulated mines with those having high explosives (without fusing). In one test,4 it was observed that 11 of 14 runs over an explosive-filled mine resulted in lower responses than "identical" runs over wax-filled mines. It was recommended that a greater in-depth study be initiated to correlate explosive-filled with inert-filled responses.

It was also noted that soil compaction by vehicle passage, especially tracked vehicles, invariably resulted in greater attenuation of the signal return. Naturally, the question arises, "Should a VMRMDS-like system be required to detect mines that have been run over several times prior to detonation? (Remotely activated mines would not necessarily detonate on first pass.)" It was recommended that this issue be examined when drafting future requirements documents.

According to Report 2412, the AN/VRS-5 signal display unit was, to say the least, not very "user friendly."

"Interpretations of the pictures on the display is subjective and requires considerable practice and familiarization . . . In the real battle scenario, the decision making by the operator would prove to be a fatiguing, traumatic experience . . . A misinterpretation of an actual live mine detection could result in a terminal detonation." 2

In summary, it is probably worthwhile to consider the final paragraph of the conclusions section of Report 2412:

"This appraisal of the AN/VRS-5 development program is somewhat critical since it is relatively easy to find flaws in hindsight. It should be remember that the pressures of schedules, funding, and personnel perturbations do not appear in the overall picture but are a large part of program management. The development of this system demonstrates clearly that the technology offers considerable promise of detecting soil/mine anomalies under proper conditions but there are definite physical limitations which must be recognized. The system, itself, could even be developed to recognize and signal these limitations." 2
PRESENT EFFORTS AND FUTURE PLANS

Because of the many attractive features of the separated aperture buried mine detection scheme, the Belvoir Countermine Technology Division has decided to initiate a new long term research program dedicated to the development of a complete understanding of the fundamental electromagnetic principles underlying this approach and to assess the general feasibility of separated aperture mine detectors.

At present, the authors of this report are conducting carefully controlled measurements at the Center's mine detection research facility. Results include measurements with both the printed circuit and broadband brass dipole antennas. To date, all experiments have been conducted in dry, loamy soil but experiments in moist and saturated soils are planned for the near future. The measurement setup and experimental results are described in detail below.

The National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards (NBS)) is under contract to the Center to provide guidance and assist Center personnel in the in-house measurement program mentioned above. They have been asked to generate a summary report of past NBS research efforts on the VMRMDS program. NIST will also provide the Center with a test fixture which can be used with the Center's Hewlett Packard 8753A RF Network Analyzer to measure the constitutive parameters (complex permittivity) of soils with varying moisture content.

The separated aperture sensor may respond to a rock or root in somewhat the same way it responds to a buried mine, resulting in an unacceptably high false alarm rate. At the present time Dr. Bernard Widrow and his graduate students at Stanford University, through support from the Center, are investigating the possibility of using a neural network with the separated aperture sensor to facilitate discrimination. Neural networks, not unlike human beings, require "training" to become proficient at a task. In this case, the neural network requires a large amount of sensor data to "learn" the difference between a buried mine and background (no mine, but possibly other mine-like objects). Recently, a fairly extensive experimental data collection program has been completed. This data has been transferred to Stanford and will be used to train a neural network to discriminate between mines and other background anomalies (clutter) and between mine types.
SECTION II. EXPERIMENTAL RESULTS

DATA COLLECTION SYSTEM

Figure 3 (see Appendix A for all figures) shows a side view of the experimental data collection system which consists of a motorized three-wheeled cart, Hewlett Packard 8753 A network analyzer, Hewlett Packard Multi-programmer, and separated aperture sensor head. A front view of the system is shown in Figure 4. The height of the sensor head above the soil surface is adjusted using the hand crank and horizontal movement of the sensor is automatically controlled by a worm gear attached to a stepper motor. As shown in Figure 5, the test equipment is controlled by a Hewlett Packard 9000 model 236 desktop computer via a fiber optic link. Experimental data collected from the network analyzer is stored on a 3.5 inch floppy disk.

BROADBAND AND PRINTED CIRCUIT SENSOR HEADS

Figure 6 shows a close-up photograph of the 790 MHz sensor head which is composed of a transmit and receive broadband dipole pair separated by a metallic septum. Each broadband dipole resides within a corner reflector. The critical dimensions of the 790 MHz sensor head and broadband dipole are given in Figure 7. A few experiments were conducted using a broadband 1 GHz sensor and the critical dimensions for this head are shown in Figure 8. A 790 MHz sensor head using printed circuit dipoles is shown in Figure 9.

The bandwidth of the 790 MHz broadband and printed circuit sensor heads of Figures 6 and 9 is examined in Figure 10. Reflection coefficient ($S_{11}$ in dB) or standing wave ratio (SWR) is measured as a function of frequency for various heights of the sensor over dry, loamy soil. Figure 10a compares the reflection coefficient ($S_{11}$ in dB) of the broadband and printed circuit dipoles for the frequency range from 300 kHz to 3 GHz when the sensors are 1 inch above the soil. Both dipoles are designed to resonate near 800 MHz and it is clear that the broadband dipole does indeed have greater bandwidth than the printed circuit dipole. An expanded view of this comparison is given in Figure 10d. Here, the SWR of the PC sensor is less than 3 from about .78 GHz to .82 GHz (a 40 MHz bandwidth), whereas the broadband sensor has an SWR less than 3 from about .75 GHz to .88 GHz (a 130 MHz bandwidth). In short, for this configuration, the broadband sensor returns less than 25% of the incident power to the source over a 130 MHz band; the PC sensor only performs that well over a 40 MHz band. Therefore, the broadband sensor has slightly more than three times the bandwidth of the PC sensor. Figures 10b and 10c demonstrate how the performance of the broadband and PC sensors vary for various sensor heights (1, 3, 5, and 7 inches).

EXPERIMENTAL PROCEDURE

This overview of the experimental test configuration defines the many variables which must be examined in order to develop a good understanding of the separated aperture dielectric anomaly.
detection scheme. Figure 11 is a scale drawing of the experimental configuration showing the 790 MHz broadband sensor parallel to and at a height $H$ above the soil surface. A dielectric anomaly, usually a 12 x 12 x 3 inch nylon block, is buried at a depth $D$ below the soil surface. For most of the experimental results presented here, the sensor head is scanned in 1.5-inch increments directly over the anomaly (receive dipole passes over the anomaly first). As shown in Figure 11, measurements are made at 27 positions for a total horizontal scan of 39 inches. At each horizontal position, the network analyzer is used to measure the transmission coefficient ($S_{21}$), complex ratio of voltage at the output of the receive dipole to the voltage at the input of the transmit dipole, at 8 MHz intervals starting at 600 MHz and ending at 1,000 MHz—51 frequency samples over a 400 MHz band. Since the dipoles are resonant near 800 MHz, the transmission coefficient is measured from 200 MHz below resonance to 200 MHz above resonance. A 6-inch septum width was used for most of the data taken with the 790 MHz broadband sensor; however, the septum width can be adjusted.

Some measurements were made with the 790 MHz sensor head rotated 90 degrees so that the transmit and receive dipoles were parallel to the scan direction. Also, a few measurements were made with the 790 MHz PC dipole sensor and the 1 GHz broadband sensor. At one point, the resonant frequency of the 790 MHz sensor was lowered to 496 MHz by extending the length of the dipole arms via a metal sleeve. No other part of the sensor head was modified. As discussed in more detail later, results with this modified sensor were not very promising. Dielectric anomalies of styrofoam and water were also examined. The water was placed in a plastic garbage bag and then carefully lowered into a hole measuring 12 x 12 x 3 inches.

SOIL AND ANOMALY CONSTITUTIVE PARAMETERS

As one might expect, the ability to detect an anomaly buried in soil depends, among other things, on how different the electrical properties of the anomaly are from those of the background soil. It also depends on how much the soil attenuates electromagnetic energy. Electromagnetic energy, which must penetrate deep into lossy earth to interact with an anomaly, will be hopelessly lost in the noise by the time it reaches the receiver.

All the experimental results presented here were conducted in fairly dry, loamy soil with a moisture content of 6% by weight. The electrical properties of the soil were measured using a shielded open circuit coaxial line technique developed by researchers at the NIST. The complex permittivity, $\varepsilon = \varepsilon' - j \varepsilon'' = \varepsilon_0 (\varepsilon_r - j \varepsilon_i)$ of the soil at 600 MHz, 790 MHz, and 1 GHz (the operating frequency range of the 790 MHz sensor) is $\varepsilon_0 (2.8842 - j 0.3712)$, $\varepsilon_0 (2.8774 - j 0.4443)$, and $\varepsilon_0 (2.8806 - j 0.5176)$, respectively, with $\varepsilon_0 = 8.854 x 10^{-12}$ F/m. It can easily be shown that a 790 MHz plane wave would be attenuated by 10 dB after propagating about 3.5 feet in this soil.
As mentioned above, dielectric anomalies of styrofoam, nylon, and water were investigated. Styrofoam has electrical properties very similar to those of air; at 10 MHz, the permittivity of styrofoam is \( \varepsilon_0 (1.03 - j 0.0002) \). A nylon block with dimensions 12 x 12 x 3 inches was used in the majority of the experiments; at 100 MHz, nylon has a permittivity of \( \varepsilon_0 (3.16 - j 0.0660) \). Few experiments were performed using water as the anomaly; water has a dielectric constant at 30\% MHz and 25°C of \( \varepsilon_0 (77.5 - j 1.25) \). Permittivity data was taken from Harrington. It is worth noting that styrofoam, nylon, and water have dielectric constants (real part of complex permittivity) less than approximately equal to, and much greater than the loamy soil background.

COUPLING AS A FUNCTION OF SENSOR HEIGHT

Figure 12 plots the transmission coefficient for the 790 MHz broadband sensor as a function of frequency for various sensor heights. Proper operation of the separated aperture sensor requires that the direct signal coupled under the airspace between the septum and earth not mask the relatively weak signal from the buried dielectric anomaly. When the sensor is close to the earth, the septum and earth function like a waveguide that is below cutoff and thus the direct signal is significantly attenuated. From Figure 12, the coupling near resonance is suppressed by about 25 dB for heights of 1, 2, and 3 inches compared with coupling at a height of 6 inches. It will be shown later that this sensor head generally does not function properly for heights greater than about 4 inches.

SOIL HOMOGENEITY AND CONTROL OF SENSOR HEIGHT

Ideally, for a fixed sensor height, the transmission coefficient vs. frequency data should be independent of horizontal sensor position provided that the soil is homogeneous. Dirt clods and packing can create background soil inhomogeneities and the sensor height will be a function of position if the soil is not level. It is important to eliminate problems such as these so that any fluctuations in measured transmission coefficient can be solely attributed to the buried anomaly.

In an attempt to remedy these problems, the entire experimental test bed was overturned with a shovel down to a depth of about 2.5 feet, and the soil was vigorously chopped with a pickax to eliminate any dirt clods. Planks 4 x 4 inches in cross section were buried and leveled at 5-foot intervals across the test area. Using another plank, the soil between these parallel planks was leveled over the entire test area. A 4 x 8 foot sheet of 5/8 inch thick plywood was laid down over one end of the test bed so that the three-wheeled cart (see Figures 3 and 4) could move up and back on a stable platform without digging ruts into the soil. In short, these precautions were taken in order to ensure that the sensor height remained constant over every horizontal scan and that the background soil was as free from inhomogeneities as possible.

Figures 13 and 14 quantify the degree to which the soil can be viewed as a homogeneous background. Figure 13 provides plots of the transmission coefficient as a function of frequency for sensor heights of 1, 2, 3, 4, 5, and 6 inches at the far left (position 1), center (position 4), and far right (position 27) of a
horizontal scan (see Figure 11). For sensor heights of 1 and 2 inches, the frequency responses at positions 1 and 14 are more or less the same (at least below 850 MHz), but the general shape of the response at position 27 seems to differ significantly from the response at positions 1 and 14, and at some frequencies by as much as 10 dB. At frequencies above 840 MHz, all three curves are somewhat different.

At sensor heights of 3 and 4 inches, the soil "looks" fairly homogeneous and at sensor heights of 5 and 6 inches, the soil "looks" perfectly homogeneous. It should be noted that as the sensor height increases, more and more energy is coupled directly through the airspace between the soil surface and septum. Thus, when the sensor height is large, the proportion of energy coupled through the soil is small compared with the direct coupled energy so that any soil inhomogeneities will be masked. (Compare the ordinate scale of Figures 13d, e, and f with those of Figures 13a, b, and c.)

Figure 14a and b provide a qualitative three-dimensional view of the soil background homogeneity as a function of frequency and position for sensor heights of 2 and 4 inches. Each figure is composed of 27 lines and each line corresponds to the transmission coefficient measured at the ith position along a horizontal scan. The first line in the foreground corresponds to the transmission coefficient measured at position 1 and the second line to measurements made at position 2, etc.

ABILITY OF 790 MHz SENSOR HEAD TO DETECT A BURIED NYLON BLOCK

Next, consider the ability of the broadband 790 MHz separated aperture sensor to detect a 12 x 12 x 3 inch nylon block buried at various depths in a background of relatively dry, loamy soil. Referring again to Figure 11, the transmission coefficient is measured at 27 positions in 1.5-inch increments across a horizontal scan for sensor heights of 1, 2, 3, 4, 5, and 6 inches, and nylon block depths of flush, 3, 6, 9, and 12 inches. (Note: The term flush indicates that the top of the nylon block is buried just under the surface of the soil, and a depth of 3 inches indicates that the top of the block is 3 inches below the soil surface, etc.) As previously mentioned, at each horizontal position, the transmission coefficient is measured at 51 discrete frequencies from 600 MHz to 1,000 MHz. The sensor dipoles are resonant near 790 MHz, and the sensor is scanned directly over the anomaly in such a way that the receive dipole passes over the anomaly first.

Transmission coefficient measurements will be a function of frequency, position, sensor height, and anomaly depth. In Figure 15, the anomaly is buried flush with the surface; in Figure 16, the anomaly is buried 3 inches deep, and so forth for Figures 17 and 18; and in Figure 19, the surface of the anomaly is 12 inches below the soil-air interface. Each figure has six plots corresponding to sensor heights of 1, 2, 3, 4, 5, and 6 inches. Each plot gives transmission coefficient (S21) vs. frequency data at sensor positions 1 (to the far left of the anomaly), 14 (directly over the anomaly), and 27 (to the far right of the anomaly).

Figures 20 through 25 display exactly the same information as Figures 15 through 19 except in a different format. In Figures 20 through 25, the sensor height is the constant parameter rather than anomaly depth. In Figure 20, the sensor height is 2 inches above the soil; in Figure 21, the sensor is
3 inches above the soil; etc. Each figure has five plots corresponding to anomaly depths of flush, 3, 6, 9, and 12 inches. Each plot gives transmission coefficient (S21) vs. frequency data at sensor positions 1, 14, and 27.

Several observations can be made from the above data. When the sensor height is less than about 4 inches, the response (S21) at position 14 is generally greater than when the sensor is at position 1 or 27. This statement is generally true over the entire frequency range from 600 MHz to 1,000 MHz; in fact, at some frequencies (Figure 15a), the difference in anomaly and background response can be as large as 25 dB.

Recall that when the sensor is close to the soil surface and over homogeneous background, the waveguide formed between the septum and soil interface is below cutoff so that direct coupling between transmit and receive dipoles is small. When the sensor is close to the earth and directly over the anomaly, the anomaly provides an additional propagation path and consequently coupling between transmit and receive dipoles increases.

When the sensor height is greater than about 4 inches, it is no longer generally true that the response at position 14 is greater than at position 1 or 27. For example (from Figure 15f), for frequencies below about 820 MHz, the response at position 14 is less than the background response, and above 840 MHz the opposite is true.

At sensor heights greater than 4 inches, the waveguide formed between the septum and soil interface is no longer below cutoff and considerable direct coupling takes place. When the sensor is directly over the anomaly, coupling through the anomaly can either constructively or destructively interfere (add in or out of phase) with the direct coupling so that the net response can either be greater or less than the background response.

The difference between the response (S21) at position 14—sensor over anomaly—and position 1 or 27—sensor away from the anomaly (the difference response)—generally decreases as the sensor height and/or anomaly depth increases. This result is expected and is merely a statement that for a given sensor height, the deeper the anomaly the harder it is to "see," and for a given depth, the anomaly becomes harder to "see" as the sensor height increases. From Figure 20, when the sensor is only 2 inches from the soil surface, the maximum difference response is at least 15 dB even when the anomaly is buried 12 inches below the surface. On the other hand, from Figure 23, when the sensor height is 4 inches above the soil, the difference response is small for anomaly depths greater than 3 inches. In short, acceptable performance can be expected for anomaly depths up to 6 inches provided the sensor height does not exceed 3 inches. This conclusion is valid only over the range of experimental conditions considered. Under different conditions (e.g., sensor design, anomaly size, soil type and moisture content, etc.) the result might be quite different. Moist or wet soil conditions, all other parameters held constant, might considerably reduce the range of anomaly depths and sensor heights over which acceptable performance could be expected.
SENSOR RESPONSE AS A FUNCTION OF POSITION

Another meaningful way to present the data obtained from the experiment depicted in Figure 11 is to plot the transmission coefficient as a function of position for fixed frequency. In Figure 26, the response vs. position of the broadband sensor at 796 MHz (the resonant frequency of the sensor dipoles) is given for sensor heights of 1, 3, 4, and 6 inches and anomaly (12 x 12 x 3 inch nylon block) depths of flush, 3, 6, 9, and 12 inches.

For sensor heights less than 4 inches and anomaly depths up to 6 inches, Figure 26 clearly shows that there is a peak in the response when the sensor is directly over the anomaly. It is also interesting to note that there is often, but not always, a dip in the response curve on either side of the peak. This phenomenon is particularly pronounced for the case when the anomaly is buried just under the soil surface (flush) and the sensor is at a height of 4 inches (see Figure 26a). In this case, the dip to the left/right of the peak occurs when the leading edge of the septum just passes over the left/right edge of the anomaly.

As expected, as the anomaly depth or sensor height increases beyond 4 and 6 inches, respectively, the peak in the response becomes washed out. The peak for an anomaly depth of 9 inches and a sensor height of 4 inches (see Figure 26d) is actually below the background level. In this case, however, the dips associated with the septum passing over the edges of the anomaly still mark its position.

Figure 27 provides plots of S21 vs. position for various sensor heights and anomaly depths similar to the results provided in Figure 26, except that sensor has been rotated 90 degrees with respect to the direction of scan. Conclusions drawn regarding Figure 26 also apply to Figure 27. The dips in the response curve again occur just as the septum passes over the edge of the anomaly. Notice that rotating the sensor has broadened the response of Figure 27a relative to that of Figure 26a. As expected, this relative broadening is less pronounced as the anomaly depth or sensor height increases. Compare Figures 26e and 27c.

Figure 28 compares the response of the 1 GHz broadband sensor, 790 MHz broadband sensor, and a sensor formed by adding metallic sleeves to the dipoles of the 790 MHz sensor so that they resonate near 500 MHz. (Note that only the length of the dipole arms were increased in developing the "500 MHz sensor"; no other part of the 790 MHz septum or corner reflector geometry was modified.) The response of the 790 MHz sensor is clearly superior to either of the other two sensors. However, for a smaller anomaly, it is quite possible that the 1 GHz sensor would provide the best performance. One problem with the 1 GHz sensor is that its response degrades rather rapidly with height in comparison with the 796 MHz sensor. The response of the 1 GHz sensor is nearly flat at a height of 4 inches and is completely washed out at 5 inches. On the other hand, the 790 MHz sensor "sees" the anomaly very well at a height of 4 inches and "sees" the anomaly somewhat even at a height of 5 and 6 inches. The performance of the 500 MHz sensor leaves much to be desired. It was originally conjectured that the
height sensitivity could be improved by lowering the resonant frequency of the 790 MHz sensor to 500 MHz. This may be true, but the test results are inconclusive since the septum and reflector geometries were not also scaled. The fact that the 6-inch septum is electrically 62.5% shorter at 500 MHz than at 790 MHz leads one to conclude that it is very likely that there is too much direct coupling from transmit to receive dipole. It may also turn out that the resolution of the sensor at 500 MHz, even if properly scaled, would be less than desirable.

Figure 29 compares the response of the broadband 790 MHz sensor with that of the 790 MHz printed circuit (PC) sensor. Since both sensors are operated at very near their resonant frequencies (790 MHz), there is very little difference in their overall performance. Because the bandwidth of the broadband dipoles is significantly greater than the PC dipoles (see Figure 10) the broadband sensor may well perform better in a detection algorithm that utilizes a wider band of frequencies. Furthermore, under stringent conditions (e.g., anomalies buried deep in moist or wet soil), one would expect bandwidth to play an even more significant role in the detection process.

Figure 30 compares the response of 12 x 12 x 3 inch anomalies of styrofoam, nylon, and water buried just under the surface of dry, loamy soil. As previously mentioned, the water anomaly was created by filling a thin plastic garbage bag with the proper amount of water so as to just fill a hole of dimensions 12 x 12 x 3 inches. It is interesting to note that the largest response occurred for the styrofoam anomaly. In fact, styrofoam gave a fairly substantial response (relative to background) even at a sensor height of 6 inches. The response when the sensor was directly over water was always greater than when the sensor was over background. For heights of 5 and 6 inches, the response when the sensor was directly over nylon was less than when the sensor was over background.
SECTION III. SUMMARY

This report provided an overview of research efforts, both past and present, with the waveguide beyond cutoff or separated aperture dielectric anomaly detection scheme. Most significantly, it was stated that this sensor exhibits the best signal-to-clutter ratio of any electromagnetic detection technique ever attempted. It was pointed out that the improved signal-to-clutter ratio is obtained when the sensor is close to the ground and consequently this detection technique is most applicable to relatively level, sparsely vegetated terrain.

Previous research efforts with the separated aperture approach, which eventually led to a Vehicle-Mounted Road Mine Detector System (VMRMDS), AN/VRS-5, were reviewed and it was pointed out that the AN/VRS-5 eventually failed because of its inability to detect mines buried deep in moist or wet soil. Other less serious deficiencies were discussed and it was concluded that the AN/VRS-5 efforts clearly demonstrated that the separated aperture technology offers considerable promise of detecting soil/mine anomalies under proper conditions, but there are definite physical limitations which must be recognized. It was pointed out that an increased operating bandwidth and frequency sampling interval might well improve the detection performance of the sensor, especially in wet soils. Furthermore, the printed circuit dipoles used in the AN/VRS-5 were inherently narrow band in comparison with the broadband brass dipoles used in the NIST research. Therefore, it was concluded that it is probably wise to use broadband brass dipoles in any further prototypes.

Present efforts and future plans were outlined. Additional experiments will be conducted at the Center's mine detection research facility by personnel in the Countermine Technology Division. Data recently collected at the Center has been transferred to Stanford University. Stanford plans to use this data to train a neural network to discriminate between mines and other background anomalies, clutter, and between mine types. The NIST has been asked to generate a summary report of past NIST research efforts on the VMRMDS program and to provide the Center with a test fixture which can be used with the Center's Hewlett Packard 8735-A Network Analyzer to measure the constitutive parameters of soils with varying moisture content.
OBSERVATIONS

In Section II of this report, the data collection system housed at the Center's mine detection research facility was described. The following important observations were made regarding the experimental data presented in this report:

1. The broadband sensor has roughly three times the bandwidth of the printed circuit (PC) sensor (see Figure 10).

2. Coupling from transmit to receive dipole is a relatively sensitive function of sensor height. Coupling near resonance (790 MHz) is suppressed by about 25 dB for sensor heights of 1, 2, and 3 inches compared with coupling at a height of 6 inches (see Figure 12).

3. In spite of efforts to eliminate dirt clods and soil packing, soil inhomogeneities were still apparent when the sensor was close (within 3 inches) to the earth. However, the return from a buried anomaly (a 12 x 12 x 3 inch nylon block buried less than 6 inches deep) is large compared with fluctuations in the return due to soil inhomogeneities.

4. A considerable amount of data was presented (see Figures 15 through 25) which characterized the ability of the 790 MHz sensor to detect a 12 x 12 x 3 inch nylon block buried in a background of relatively dry, loamy soil. Transmission coefficient data was presented as a function of frequency for sensor heights of 1, 2, 3, 4, 5, and 6 inches and nylon block depths of flush, 3, 6, 9, and 12 inches. Acceptable performance (the anomaly was "visible") can be expected for anomaly depths up to 6 inches provided the sensor height does not exceed 3 inches.

5. The sensor response as function of position at the resonant frequency of the sensor showed (see Figure 26) that there is a peak in the response when the sensor is directly over the anomaly and that there is a dip or null on either side of the peak. The dip to the left/right of the peak occurs when the leading edge of the septum just passes over the left/right edge of the buried anomaly. As the anomaly depth or sensor height increases beyond 6 and 4 inches, respectively, the peak in the response becomes washed out.

6. Rotating the sensor with respect to the direction of scan (see Figure 27) does not appreciably change the response.

7. The 790 MHz sensor performed better than either the 1 GHz or 500 MHz sensors (see Figure 28). For small anomalies, the 1 GHz sensor may perform best. The 500 MHz sensor may have performed better if the entire 790 MHz sensor was scaled—not just the dipoles.

8. As demonstrated in Figure 29, the broadband sensor performed about as well as the PC sensor. Over a broader range of frequencies, the broadband sensor would probably perform better than the PC sensor.

9. Figure 30 compares the response of 12 x 12 x 3 inch anomalies of styrofoam, nylon, and water buried just under the surface of dry, loamy soil. The largest response (relative to background) was obtained from the styrofoam anomaly.
RECOMMENDATIONS FOR FURTHER RESEARCH

The experimental data discussed in this report represents, at best, only a first order effort at completely characterizing the performance of the separated aperture dielectric anomaly detection scheme. Additional experiments will be required in order to gain a more complete comprehension of the operating characteristics and inherent limitations of this sensor.

As previously mentioned, the most serious problem with the AN/VRS-5 was its extremely poor detection rate of mines buried in high-moisture content soils. It was also conjectured that the broadband sensor would perform better than the PC sensor in moist or wet soils. Therefore, it is recommended that experiments conducted with the 12 x 12 x 3 inch nylon block be repeated in moist soils with both the broadband and PC sensor heads.

Most of the experimental data presented in this report dealt with the ability of the 790 MHz broadband sensor to detect a 12 x 12 x 3 inch nylon block buried in a background of dry, loamy soil. The 12 x 12 x 3 inch anomaly is about the same size as an antivehicular mine. Antipersonnel mines are typically smaller than antivehicular mines so that additional experimental data with a smaller anomaly and the 1 GHz sensor head would be required to optimize sensor design for detection of antipersonnel mines.

A considerable amount of experimental data was generated by NIST on the old VMRMDS program and, as previously mentioned, NIST is presently generating a written summary of these efforts. With this document in hand, it will be much easier to make an accurate assessment of the present state of the experimental database and to identify areas requiring further experimental efforts. Also, a substantially expanded experimental effort may be warranted depending on the relative success of the Stanford neural network research.

It is not difficult to see that an enormous experimental effort is required to completely characterize sensor performance. Unfortunately, even a thorough measurement program will not necessarily provide an adequate understanding of the fundamental mechanisms which control the detection process. Experimental techniques provide the "answer" but they do not necessarily provide a reason for the "answer." Therefore, it is recommended that a theoretical analysis be initiated with the goal of providing a complete understanding of the fundamental electromagnetic principles underlying the separated aperture mine detection technique.

In summary, a carefully orchestrated theoretical and experimental effort will probably provide the best possible opportunity to select optimum design specifications for a close-in mine detection prototype based on the separated aperture detection technique.
REFERENCES


## APPENDIX A
### ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simple schematic of the separated aperture or waveguide beyond cutoff mine detection system. When the sensor is over homogeneous earth (no mine present), very little power is received. There is a significant increase in received power when the sensor is over a mine. Best mine detection performance requires careful optimization of sensor parameters (i.e., sensor height, septum width, etc.)</td>
<td>A-6</td>
</tr>
<tr>
<td>2</td>
<td>Close-in front view of AN/VRS-5 detector</td>
<td>A-7</td>
</tr>
<tr>
<td>3</td>
<td>Side view of experimental setup consisting of motorized three-wheeled cart, Hewlett Packard 8753-A network analyzer and multi-programmer, and separated aperture sensor head</td>
<td>A-8</td>
</tr>
<tr>
<td>4</td>
<td>Front view of experimental test setup showing sensor head, hand crank to control height of sensor head above earth, and carriage with worm gear for horizontal movement of sensor head</td>
<td>A-91</td>
</tr>
<tr>
<td>5</td>
<td>Hewlett Packard 9000 Model 236 desktop computer used to control, via a fiber optic link, the experimental test setup of Figures 3 and 4. Experimental data collected from the network analyzer is stored on a 3 1/2 inch floppy disc</td>
<td>A-10</td>
</tr>
<tr>
<td>6</td>
<td>Close up photograph of 790 MHz sensor head, composed of a transmit and receive broadband dipole pair, separated by a metallic septum; each broadband dipole resides within a corner reflector</td>
<td>A-11</td>
</tr>
<tr>
<td>7</td>
<td>Critical dimensions of 790 MHz sensor head and 790 MHz broadband dipole</td>
<td>A-12</td>
</tr>
<tr>
<td>8</td>
<td>Critical dimensions of 1 GHz sensor head and 1 GHz broadband dipole</td>
<td>A-13</td>
</tr>
<tr>
<td>9</td>
<td>Close-up photograph of 790 MHz head, composed of a transmit and receive printed circuit (PC) dipole pair, separated by a metallic septum; each PC dipole resides within a corner reflector</td>
<td>A-14</td>
</tr>
<tr>
<td>10</td>
<td>Reflection coefficient (S11 dB) or standing wave ratio (SWR) as a function of frequency for broadband and printed circuit (PC) dipoles. Measurements were made with the dipoles in the sensor head (see Figures 6 and 9) with the sensor head at various heights above the earth (dry, loamy soil): a) broadband dipole (-----), PC dipole (- - - -) for a 1 inch sensor height b) broadband dipole for sensor heights of 1, 3, 5, and 7 inches c) PC dipole for sensor heights of 1, 3, 5, and 7 inches d) broadband dipole (-----), PC dipole (-----) for a sensor height of 1 inch</td>
<td>A-15</td>
</tr>
</tbody>
</table>
Scale drawing of experimental configuration showing 790 MHz sensor head (see Figure 6) parallel to and at a height \( H \) above the soil surface and dielectric anomaly (12 x 12 x 3 inches) buried at depth \( D \) below the soil surface. The sensor head is scanned directly over the anomaly in the direction shown (receive dipole passes over the anomaly first) in 1.5-inch increments for a total horizontal scan of 39 inches. The broadband dipoles are resonant at 790 MHz (see Figure 10). The sensor head septum width is adjustable in 1-inch increments over a range from 1 to 6 inches; however, for most of the data shown here, the septum width is held fixed at 6 inches.

Measurement of transmission coefficient \((S_{21})\) as a function of frequency over dry, loamy soil for broadband sensor heights of 1, 2, 3, 4, 5, and 6 inches; no dielectric anomaly present.

Measurement of transmission coefficient \((S_{21})\) as a function of frequency over dry, loamy soil with no dielectric anomaly present. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center and far right of a 39-inch horizontal scan. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.

Measurement of transmission coefficient \((S_{21})\) as a function of frequency and sensor position. The broadband sensor is scanned over dry, loamy soil at a height of: a) 2 inches; b) 4 inches.

Measurement of transmission coefficient \((S_{21})\) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried flush with the surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.

Measurement of transmission coefficient \((S_{21})\) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 3 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 6 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil..............................................................................A-22</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 9 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil..............................................................................A-23</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 12 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil..............................................................................A-24</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 1 inch above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.......................................................................................................................................A-25</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 2 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.......................................................................................................................................A-26</td>
<td></td>
</tr>
</tbody>
</table>
Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 3 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.

Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 4 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.

Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 5 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.

Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 6 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.

Measurement of transmission coefficient ($S_{21}$) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipole. The receiving dipole passes over the nylon block first.
27 Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipoles. The sensor head passes oriented so that the transmit and receive dipoles are parallel to the scan direction .................................................. A-32

28 Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The receiving dipole passes over the nylon block first. The transmission coefficient is measured near the resonant frequency of the broadband dipoles at: a) 1 GHz; b) 796 MHz; c) 496 MHz ............................................................................. A-33

29 Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the: a) broadband dipole; b) printed circuit (PC) dipole sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is near the resonant frequency of the broadband and PC dipoles. In each case, the receiving dipole passes over the nylon block first ................................................................................................................. A-34

30 Measurement of transmission coefficient (S21) as a function of position for various anomalies, 1 - styrofoam, 3 - nylon, 4 - water, buried flush with the surface of dry loamy soil. The transmission coefficient is measured 796 MHz which is near the resonant frequency of the broadband dipoles. In each case, the receiving dipole of the sensor passes over the anomaly first. The sensor head is: a) 2 inches; b) 3 inches; c) 4 inches; d) 5 inches; e) 6 inches above the soil surface .................................................................................................................. A-35
Figure 1. Simple schematic of the separated aperture or waveguide beyond cutoff mine detection system. When the sensor is over homogeneous earth (no mine present), very little power is received. There is a significant increase in received power when the sensor is over a mine. Best mine detection performance requires careful optimization of sensor parameters (i.e., sensor height, septum width, etc.)
Figure 2. Close-in front view of AN/VRS-5 detector
Figure 3. Side view of experimental setup consisting of motorized three-wheeled cart, Hewlett Packard 8753-A network analyzer and multi-programmer, and separated aperture sensor head.
Figure 4. Front view of experimental test setup showing sensor head, hand crank to control height of sensor head above earth, and carriage with worm gear for horizontal movement of sensor head.
Figure 5. Hewlett Packard 9000 Model 236 desktop computer used to control, via a fiber optic link, the experimental test setup of Figures 3 and 4. Experimental data collected from the network analyzer is stored on a 3 1/2 inch floppy disc.
Figure 6. Close up photograph of 790 MHz sensor head, composed of a transmit and receive broadband dipole pair, separated by a metallic septum; each broadband dipole resides within a corner reflector.
Figure 7. Critical dimensions of 790 MHz sensor head and 790 MHz broadband dipole
Figure 8. Critical dimensions of 1 GHz sensor head and 1 GHz broadband dipole
Figure 9. Close-up photograph of 790 MHz head, composed of a transmit and receive printed circuit (PC) dipole pair, separated by a metallic septum; each PC dipole resides within a corner reflector.
Figure 10. Reflection coefficient (S11 dB) or standing wave ratio (SWR) as a function of frequency for broadband and printed circuit (PC) dipoles. Measurements were made with the dipoles in the sensor head (see Figures 6 and 9) with the sensor head at various heights above the earth (dry, loamy soil):

a) broadband dipole (---), PC dipole (——) for a 1 inch sensor height
b) broadband dipole for sensor heights of 1, 3, 5, and 7 inches
c) PC dipole for sensor heights of 1, 3, 5, and 7 inches
d) broadband dipole (——), PC dipole (——) for a sensor height of 1 inch
Figure 11. Scale drawing of experimental configuration showing 790 MHz sensor head (see Figure 6) parallel to and at a height H above the soil surface and dielectric anomaly (12 x 12 x 3 inches) buried at depth D below the soil surface. The sensor head is scanned directly over the anomaly in the direction shown (receive dipole passes over the anomaly first) in 1.5-inch increments for a total horizontal scan of 39 inches. The broadband dipoles are resonant at 790 MHz (see Figure 10). The sensor head septum width is adjustable in 1-inch increments over a range from 1 to 6 inches; however, for most of the data shown here, the septum width is held fixed at 6 inches.
Figure 12. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil for broadband sensor heights of 1, 2, 3, 4, 5, and 6 inches; no dielectric anomaly present.
Figure 13. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil with no dielectric anomaly present. In each figure curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center and far right of a 39-inch horizontal scan. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 14. Measurement of transmission coefficient ($S_{21}$) as a function of frequency and sensor position. The broadband sensor is scanned over dry, loamy soil at a height of: a) 2 inches; b) 4 inches
Figure 15. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried flush with the surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 16. Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 3 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 17. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 6 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 18. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 9 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 19. Measurement of transmission coefficient ($S_{21}$) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. A nylon block (12 x 12 x 3 inches) is buried 12 inches below the soil surface so that the broadband sensor head is centered directly over the nylon block at position 14. The broadband sensor is: a) 1 inch; b) 2 inches; c) 3 inches; d) 4 inches; e) 5 inches; f) 6 inches above the soil.
Figure 20. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 1 inch above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 21. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 2 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 22. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 3 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 23. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 4 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 24. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curves 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 5 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 25. Measurement of transmission coefficient (S21) as a function of frequency over dry, loamy soil. In each figure, curved 1, 14, and 27 correspond, respectively, to the sensor head at the far left, center, and far right of a 39-inch horizontal scan. The broadband sensor is 6 inches above the soil. A nylon block (12 x 12 x 3 inches) is buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/ below the soil surface so that the broadband sensor is centered directly over the nylon block at position 14.
Figure 26. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipole. The receiving dipole passes over the nylon block first.
Figure 27. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried: a) flush; b) 3 inches; c) 6 inches; d) 9 inches; e) 12 inches with/below the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is nearly resonant frequency of the broadband dipoles. The sensor head passes oriented so that the transmit and receive dipoles are parallel to the scan direction.
Figure 28. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the broadband sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The receiving dipole passes over the nylon block first. The transmission coefficient is measured near the resonant frequency of the broadband dipoles at: a) 1 GHz; b) 796 MHz; c) 496 MHz
Figure 29. Measurement of transmission coefficient (S21) as a function of position for various sensor heights (1, 3, 4, and 6 inches as indicated) as the: a) broadband dipole; b) printed circuit (PC) dipole sensor head is scanned over a nylon block (12 x 12 x 3 inches) buried flush with the surface of dry, loamy soil. The transmission coefficient is measured at 796 MHz which is near the resonant frequency of the broadband and PC dipoles. In each case, the receiving dipole passes over the nylon block first.
Figure 30. Measurement of transmission coefficient (S21) as a function of position for various anomalies, 1 - styrofoam, 3 - nylon, 4 - water, buried flush with the surface of dry loamy soil. The transmission coefficient is measured 796 MHz which is near the resonant frequency of the broadband dipoles. In each case, the receiving dipole of the sensor passes over the anomaly first. The sensor head is: a) 2 inches; b) 3 inches; c) 4 inches; d) 5 inches; e) 6 inches above the soil surface.
APPENDIX B

COMPUTER CONTROL/DATA COLLECTION SOFTWARE
C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.

FF

C. EY. MEL.
C.

IMPjL

"WHoT

"AVEGUIDE

148S

OR

C1610:

"Wa'veguiaes

eag

INPUT

'DIELECT:

mi4TEP!.AL

IS

BEI'rZ

TESTED?

.1

108c6-tIcs

JI:PUT

"HOW

DEEP

1:1

ANOMlALY

BURIED!

tI

CHES

d

S

PR

IH Er"S

THIS TEST

Ati

AREA

CA

OP

1.E

OR

IT

XEC-

POZ-I

ITiOr,

SCir4

S.C

mi.'SCAN,

I

*Dý

11

INPLT

P.;;

it io

n

1

IF

Pc

-"Ai.CAN"0

OR

P,)stijn1-"SCkt.' OP PosItioni-FI;<ED" THE14

800

-~

]:9:;.PIUT

ERPCP.

.. 0

PP~t4T

TP

Gm';MII

M;`P

_ F

PU

T

Rel

ppnss

I

0

CLXrP.P

SC :ZEEN

10

IF Feipon5e$0

'Y T-iE!4

o80

PR -'4T 1PPOGPAfr OISC:,NTIflUED.,

.90

STOP

8R3

F

Posit.n.;CN

THEN

Iaqw2

8310

IF i::,Fdy'THEN

3'.

Flag-

84C,

ItPU-T LJIWhT

ýqPE

MEý,SuREr1EN
4P~0EMENTS! k.INCHES",IncrementsS

3ý(. Incremen!-5UALt Increment~s)

9120

IF Flag-.: THEh INi:UT

'HOW

MAN?

INCREmr1ENS

IS CkJT

TO

10,"

Scanner

930

Ii4PU`

"NA.-E

OF F>..E7",One$

940

INPUT

"REH.d TO

COLLECT

DAT0~

.

),GoS

50

IF

Go$-'i" THEN 990

960

CLE-'4R

SCPEEN

ý"()

DI;P

"PROGRpci

HAS

BEENJ

-8OR'ED."

980

STOF

;iao

IF

Flag-:

THEN

100)

FCR

J-37

TO0 Scarnbr

1020

Column=Readings

1030

Rowcheck:=2

1040

IF Rowcheck=2 THEN Rowcheck:=1

1050

FOR I=1 TO Readings

1060

IF Flag=0 THEN 1070

1070

FCR Z=1 TO 10

1080

ON KEY 1 LABEL ABORT",1 GOTO 2*0

1090

NET Z

1100

KEY LABELS ON

1110

ASSIGN B: TO "l;a:FORMAT" OFF

1120

IF Flag=1 THEN

1130

INPUT "HIT ANY KEY TO PROCEED",Wait#

1140

OUTPUT 75=s"NUMGS="AUTO:FC:18:OUTPHN1":";

1150

ELSE

1160

(OUTPUT "l:o;"NUMS:"FORM:;OUTPATH;"

1170

END IF

1180

ENTER (B:4eLth,Set")

1190

IF Flag=2 THEN

1200

IF Rowcheck=2 THEN

1210

Z=Z-MIColumn:

1220

ELSE

1230

Z=Z+1:

1240

END IF

1250

GOTO 1030

1260

Treat One IF RCIPUL 1 TO 2

1270

ELSE

1280

"This is blank",B:3

B-3
1300 ELSE IF
1310 CLEAR "THIS IS FILE 4-44 INCLUDINg MEASUREMENT NUMBER: ".
1320 GOTO BLANK "tree", 3
1330 ASSIGN BLANK TO Tree
1340 OUTPUT @iiscan.Lth.Pct:
1350 IF Print=0 THEN 1500
1360 OUTPUT "10, CLOTHED:";
1370 OUTPUT "20. LEAD-SC APPLIED:";
1380 ELSE SPILL="t":
1390 IF NOT BIT 8. THEN GOTO 1380
1400 ELSE "It is CLOTH":
1410 CLEAR PRINTING CAT NAME FROM NETWORK ANALYZER"
1420 STAINS "simple"
1430 IF NOT BIT 12.d=1 THEN GOTO 1420
1440 PRINTER IS "Y"
1450 FOR i=1 TO 1
1460 PRINT "CHR=10"
1470 NEXT
1480 IF Print=1 THEN "FILE NAME IS ": "tree"
1490 PRINT "WAVEGUIDE IS: ".
1500 PRINT "P4-T{E4", Cread=0:true"
1510 IF F.flag="T" THEN
1520 PRINT "WAVEGUIDE HEIGHT ABOVE GROUND IS 2", Heights," INCHES"
1530 ELSE
1540 PRINT "WAVEGUIDE HEIGHT ABOVE GROUND IS ": Heights," INCHOES"
1550 END IF
1560 IF Electric="T" THEN
1570 PRINT "DIELECTRIC MATERIAL TESTED IS: ".
1580 PRINT "POSITIONING OVER TARGET IS: ".
1590 PRINT "RESOLUTION OF POSITIONING IS EQUP: Increment"," INCHES"
1600 (Increment="Y", Increment="T"
1610 PRINT "NUMBER OF MEASUREMENT INCERRORS IS: ", Number="I"
1620 PRINT "THE DISTANCE FROM THE SOIL SURFACE TO THE TOP OF THE DIELECTRIC MANIFOLD IS: ", Distance," INCHES"
1630 PRINT "CHR=12"
1640 IF Print=1 THEN "Column=Column-1"
1650 IF Readings<0 OR Position="FILED" THEN 1710
1660 IF PouchFlag=1 THEN
1670 GO SUB Left EAR
1680 ELSE
1690 GOSUB Right
1700 END IF
1710 NEXT I
1720 IF J MOD 0 = 0 THEN 1720
1730 IF DISC HAS BEEN CHANGED.HIT TEXT TO CONTINUE": GO
1740 IF Flag = 2 THEN 1720
1750 IF J=Scanner THEN 1760
1760 GO SUB Carton
1770 NEXT I
1780 KEY LABELS OFF
1790 Distance="Readings Increment"
1800 DISP
1810 PRINT "CHR=10"
1820 CLEAR SCREEN
1830 PRINT "LIST IS STORED. PROGRAM IS DONE."
1840 PRINT
1850 IF Position="FILED" THEN ENO
1860 PRINT "WAVEGUIDE IS NOE: ", Distance," INCHES"
1870 KEY LABELS ON
1880 STOP
1890 Pertain=1
1900 IF AntiFlag="TEN THEN
1910 OUTPUT @list.OP 0,5,17:" HIGH CURRENT
1920 WAIT .1
1930 OUTPUT @list.OP 0,5,17:" HIGH CURRENT

Copy available to DTIC does not
Permit fully legible reproduction.
1100 1120 1140 1160 1180 1200 1220 1240 1260 1280 1300 1320 1340 1360 1380 1400 1420 1440 1460 1480 1500 1520 1540 1560 1580 1600 1620 1640 1660 1680 1700 1720 1740 1760 1780 1800 1820 1840 1860 1880 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200 2220 2240 2260 2280 2300 2320 2340 2360 2380 2400 2420 2440 2460 2480 2500 2520 2540 2560 2580 2600 2620 2640 2660 2680 2700 2720 2740 2760 2780 2800 2820 2840 2860 2880 2900 2920 2940 2960 2980 3000 3020 3040 3060 3080 3100 3120 3140 3160 3180 3200 3220 3240 3260 3280 3300 3320 3340 3360 3380 3400 3420 3440 3460 3480 3500 3520 3540 3560 3580 3600 3620 3640 3660 3680 3700 3720 3740 3760 3780 3800 3820 3840 3860 3880 3900 3920 3940 3960 3980 4000 4020 4040 4060 4080 4100 4120 4140 4160 4180 4200 4220 4240 4260 4280 4300 4320 4340 4360 4380 4400 4420 4440 4460 4480 4500 4520 4540 4560 4580 4600 4620 4640 4660 4680 4700 4720 4740 4760 4780 4800 4820 4840 4860 4880 4900 4920 4940 4960 4980 5000

Copy available to DTIC does not permit fully legible reproduction.
2160 =. "\"if distance=0 THEN\" OUTPUT "\"C\";OP \"11,6517,T\" 2170 ELSE OUTPUT "\"C\";OP \"11,6519,T\" 2180 END IF OUTPUT "\"C\";OP \"9,1,40000T,WC,14,2,40000T\" 2190 FOR X=0 TO 483 Distance=STEP Rate=5 2200 OUTPUT "\"C\";OP 3,5,14,5,T\" 2210 NEXT X 2220 OUTPUT "\"C\";OP 11,5552e,T\" 2230 SUBEND

Copy available to DTIC does not permit fully legible reproduction

B-6
Block Diagram of Data Collection System
APPENDIX C
PLOTTING SOFTWARE

This program is designed to extract, convert, and plot data collected in real and imaginary number form.

100 OPTION BASE 1
110 PRINT "WELCOME TO THE REI PLOTTING PROGRAM FOR HE-DATA"
120 RESTORE
130 INTEGER CNT, HR, Lc, L, N
140 DIM Bati(FILE), Plot(FILE)
150 DATA "File"
160 DATA 10".
170 DATA "Name"
180 DATA 10".
190 DATA "Size"
200 DATA 10".
210 DATA "Input"
220 DATA 10".
230 DATA "Plot"
240 DATA 10".
250 DATA "Output"
260 DATA 10".
270 DATA "Title"
280 DATA 10".
290 DATA "Title"
300 DATA 10".
310 DATA "Input"
320 DATA 10".
330 DATA "Plot"
340 DATA 10".
350 DATA "Output"
360 DATA 10".
370 DATA "Title"
380 DATA 10".
390 DATA "Title"
400 DATA 10".
410 DATA "Input"
420 DATA 10".
430 DATA "Plot"
440 DATA 10".
450 DATA "Output"
460 DATA 10".
470 DATA "Title"
480 DATA 10".
490 DATA "Title"
500 DATA 10".
510 DATA "Input"
520 DATA 10".
530 DATA "Plot"
540 DATA 10".
550 DATA "Output"
560 DATA 10".
570 DATA "Title"
580 DATA 10".
590 DATA "Title"
600 DATA 10".
610 DATA "Input"
620 DATA 10".
630 DATA "Plot"
640 DATA 10".
650 DATA "Output"
660 DATA 10".
670 DATA "Title"
680 DATA 10".
690 DATA "Title"
700 DATA 10".
710 DATA "Input"
720 DATA 10".
730 DATA "Plot"
740 DATA 10".
750 DATA "Output"
760 DATA 10".
770 DATA "Title"
780 DATA 10".
790 DATA "Title"
800 DATA 10".
810 DATA "Input"
820 DATA 10".
830 DATA "Plot"
840 DATA 10".
850 DATA "Output"
860 DATA 10".
870 DATA "Title"
880 DATA 10".
890 DATA "Title"
900 DATA 10".
910 DATA "Input"
920 DATA 10".
930 DATA "Plot"
940 DATA 10".
950 DATA "Output"
960 DATA 10".
970 DATA "Title"
980 DATA 10".
990 DATA "Title"

C-1
C-2
1270 LINE 1,300 
1280 END IF 
1290 NEXT N 
1300 IF I = 0 
1310 NEXT I 
1320 END IF 
1330 END 
1340 END THE GEN IS COMPLETE. YOU CAN USE THE BASIC SYSTEM AGAIN.
DISTRIBUTION FOR REPORT NO. 2497

DEPARTMENT OF DEFENSE

1 Commander
US Army Electronics Research & Development Command
ATTN: DELSD-L
Fort Monmouth, NJ 07703-5301

1 HQ 193D Infantry Brigade (Panama)
ATTN: AFZU-FE
APO Miami 34004

DEPARTMENT OF THE ARMY

1 Defense Technical Information Center
Cameron Station
ATTN: DTIC-FDAC
Alexandria, VA 22304-6145

1 Special Forces Detachment, Europe
ATTN: PBO
APO New York 09050

1 HQDA (DAMA-AOA-M)
Washington, DC 20310

1 Commandant
US Army Engineer School
ATTN: ATZA-CDD
British Liaison Officer

1 ATTN: ATSE-DAC-LB
Fort Leonard Wood, MO 65473

1 President
US Army Armor and Engineer Board
ATTN: ATZK-AE-PD-E
Fort Knox, KY 40121-5470

1 US Army Engineer School
ATTN: AMCPMPWL
Public Affairs Office

4300 Goodfellow Blvd.
St. Louis, MO 63120

Distribution-1