SUBSURFACE ELECTROMAGNETIC TARGET CHARACTERIZATION
AND IDENTIFICATION

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THIS DOCUMENT IS BEST QUALITY PRACTICABLE. THE COPY FURNISHED TO DDC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.
A method for subsurface radar target characterization and identification is described. This method characterizes subsurface radar targets by their complex natural resonances which are extracted directly from their backscattered time-domain waveforms. The difference equation coefficients associated with the complex resonances are then used in the predictor-correlator for target identification. Both the characterization and identification processes are extensively tested with real radar measurements and found to yield practical target identification performance. The target identification process is simple and involves...
only simple algebraic operations. Based on the identification process, a "first-generation" microcomputer identification radar system is implemented for target identification in real time. This radar system is found to yield practical identification performance.
ACKNOWLEDGMENTS

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The material contained in this report is also used as a dissertation submitted to the Department of Electrical Engineering, The Ohio State University as partial fulfillment for the degree Doctor of Philosophy.
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CHAPTER I
INTRODUCTION

A. Research Goals

Subsurface radar detection and identification of geological and man-made structures is an area of current importance. Examples are: location of utility pipes such as plastic and metallic gas pipes and water pipes[1,2,3], location of voids and tunnels[4], anthropology mapping[5], and possible exploration of energy sources such as oil, gas and coal. Yet, almost all of the work done in this area was directed toward target detection. Few attempted the problem of target identification. Subsurface target identification is a problem far more severe than the identification of aerospace targets by conventional radars where the target can literally be seen and the class of false targets is limited in scope. Underground there are varieties of unknown false or undesired targets to complicate the task. Furthermore, the medium involved, i.e., the ground, is usually lossy, inhomogeneous and, most of all, electrically weather-dependent. These problems, together with the presence of the air-ground interface makes the task of subsurface target identification truly formidable. It is for these reasons that, to date, there is no single technique or system capable of identifying subsurface targets in real time.

In this study, a technique for subsurface target identification is developed and extensively tested with real radar measurements collected using a video pulse radar[1-4] under different conditions (i.e., different ground conditions, different antennas, etc.). This technique is implemented with a "first-generation" microcomputer system to demonstrate the feasibility of real-time subsurface target identification.

The technique used in this study characterizes subsurface targets by their complex natural resonances[7-11], which are extracted directly from the processed time domain waveforms via Prony's Method[12-15]. A predictor-corrector[40] uses the difference equation coefficients associated with these complex resonances as discriminants to generate a correlation coefficient for target identification. This characterization and identification method is attractive for it characterizes the response of a target by a set of complex numbers which is independent of the pulse radar location. Furthermore, the complex resonances and the difference equation coefficients are pre-determined, thus, only simple algebraic operations are involved in calculating the correlation coefficient for a real-time identification decision.
B. Related Research in Subsurface Target Characterization and Identification

Electromagnetic techniques have been used successfully for many years for probing the earth. Keller and Freschnecht[25] give an excellent summary of these procedures. A recent summary of subsurface probing techniques is given in a report by D.C. Gates, et al[26].

Perhaps the earliest documentation of a subsurface electromagnetic radar system is contained in a patent issued in 1937 in which an electrical analog of seismic systems is described[16]. There is, however, no mention of successful implementation of such a radar. There have been attempts to use bistatic radar configurations of this type but the results have generally not been highly successful[17,18]. The reason, recognized by Horton[19], is that the tail of the pulse coupled directly from the transmit to the receive antenna occurs "just at the time when the maximum of the reflected pulse (from a buried target) must be accurately timed. This coincidence tends to ruin the measurement".

A significant result in video pulse technology is described in a patent by Lerner in which a video pulse system is used for more moderate depths[20]. Lerner's scheme differed from the earlier patent in that the same antenna was used for both transmitting and receiving. Lerner introduced a combination of TR, ATR and Hybrids to separate the transmitted pulse and the received target signal.

In this study, a crossed-dipole antenna system is used to incorporate this function into the antenna itself, i.e., transmit-receive isolation is achieved by isolating the antennas themselves. The crossed dipole is an orthogonal dipole pair, one horizontal dipole for transmission and another orthogonal horizontal dipole for reception, which provides substantial reduction of the primary (directly coupled) signal on the receiving antenna. Many measurements have been made on a variety of shallow targets (less than 15 m) using these concepts[1-4,21,22]. Targets include geological structures such as faults, joints, sink holes and man-made structures such as pipes. A commercial unit for pipe detection based upon the research and design work at the ElectroScience Laboratory, and designated as Terrascan, is being produced by Microwave Associates Inc.[6]. The pulse radar used in this study for subsurface target identification is a Terrascan-like radar system.

A major reason for the success of the characterization and identification procedures discussed in this dissertation lies in the improvements in the antenna system. The original cross-type antenna structure developed at the ElectroScience Laboratory for subsurface radar applications was basically a crossed bowtie geometry wrapped around a sphere[21], but this was subject to noise. The crossed bowtie
evolved into various planar crossed-dipole arrangements as used by Moffatt[4]. These arrangements were, however, too awkward for use in real-time on-location target identification. Later, Young[1,3] introduced the loaded folded dipole geometry of the Terrascan system. Tribuzi[66] improved this by introducing the loaded folded bowtie configuration. Wald[59] further improved the electrical characteristics of this structure by eliminating part of the supporting structure. He also constructed the small antenna used in a later part of this dissertation for identification of mines. The design of the smaller antenna was dictated by the results obtained in this dissertation since its purpose was to shift the antenna resonance to more nearly coincide with those of the mine-like target.

One of the first studies initiated in the development of the pulse radar system with the crossed-dipole antenna for subsurface target detection and identification was the detection and identification of TDMB mines[28-35]. This study included efforts in the development of antenna systems and techniques to extract the characteristic spectra of the electromagnetic fields scattered by the TDMB mine. In 1970, Sullivan[21] investigated the feasibility of using the characteristic real-frequency resonances of subsurface targets in the identification of simple buried objects. The system used in Sullivan's study was a video pulse radar with a crossed-polarized antenna system. A similar system using crossed dipoles was later used by Moffatt, et al.[4] in the probing of man-made and geological subsurface targets. The subsurface video pulse radar system was then modified and developed to be the existing Terrascan system in a study to detect gas pipes[1-3]. To automate the Terrascan system for automatic target identification, Chan[22] investigated a matched filter technique for automatic identification of plastic pipes using a Terrascan-like radar system.

Other methods have been employed in the detection and identification of subsurface targets. In particular, various techniques of Pattern recognition[37-39] were used by Echard, et al. for the detection and identification of buried mines[36].

This study investigated the possibility of using in situ target complex natural resonances to characterize and identify subsurface targets. The basic method was first introduced by Hill[40] in the detection of targets near the surface of the earth, and later used by Chan, et al.[23,48-50] in the characterization and identification of subsurface targets.
C. Structure of This Report

The structure of this report is as follows:

In chapter II, the basic radar measurement procedure is presented. In addition, preliminary signal processing is discussed since certain preprocessing does improve the target identification results.

In Chapter III, we present a method for extracting from response data records (i.e., the time-domain waveforms) the complex natural resonances associated with the targets. This method, known as Prony's method, is outlined and applied to extract target resonances from the backscattered waveforms in the time domain.

In Chapter IV, the predictor-correlator method for target identification is discussed and applied to the waveforms collected in this study. Detailed identification statistics are given.

In Chapter V, the effects of radar bandwidth on the characterization and identification method are studied.

In Chapter VI, the effects of target size and depth on the characterization and identification method are discussed.

In Chapter VII, we direct attention to the detection and identification of mine-like targets in practical situations. Improvements on the pulse radar system are made for the implementation of a portable, real-time on-location subsurface target identification radar.

In Chapter VIII, we discuss the implementation of the subsurface identification radar as a microcomputer system. Detailed procedures of the implementation are presented. Real-time target identification results using the microcomputer system are given.

In Chapter IX, a method for automatic tuning of the identification radar to the ground condition in real time is discussed. This method is simple and can be easily incorporated into the microcomputer system for real-time subsurface target identification.

In Chapter X, major achievements accomplished in this work are summarized. Conclusions and recommendations are made.
CHAPTER II
MEASURED AND PROCESSED WAVEFORMS
FROM THE SUBSURFACE TARGETS

A. Objectives

The objectives of this chapter are the following:

1. To give a description of the subsurface pulse radar and the subsurface targets selected for this study and to summarize the procedures taken to measure the back-scattered waveforms from these targets. Raw (unprocessed) waveforms from the targets are shown.

2. To summarize the signal-processing techniques used to partially suppress noise and clutter in the raw waveforms. Processed waveforms are given.

B. Subsurface Electromagnetic Video Pulse Radar System

The video pulse radar system used to collect measurements for this study basically consists of three components: the energy source, the antenna system for signal transmitting and receiving and the receiver for signal processing. The design of these components is dictated by the electrical properties of the ground, the depth of the target of interest as well as the target, clutter and noise characteristics. A picture of the Terrascan-like subsurface pulse radar used in this study together with a basic block diagram is shown in Figure 1. The basic components are: the impulse generator, the crossed-dipole antenna system and the receiver. Basic operation is as follows. The impulse generator transmits short pulses of energy through the transmit antenna into the ground. The presence of a target scatters the incident energy toward the receive antenna. This scattered energy is received as a sampled time-domain waveform for target characterization and identification.

In the current study a short video pulse of approximately 150 ps duration (at 3 dB points) and a nominal 1000V peak amplitude was used (see Figure 2). This pulse duration is much shorter than those used in conventional radar practice. Furthermore, a conventional radar has a few percent bandwidth about its carrier
Figure 1. The subsurface pulse radar and its block diagram.
Figure 2. Characteristics of the impulse source in time and frequency domain.
frequency whereas this video pulse output spectrum spreads from essentially dc (repetition rate = 256 Hz) to beyond 3 GHz. It is this broad band of frequencies inherent in this narrow pulse that makes target identification a possibility, i.e., the scattered fields from the targets can be sampled over a very broad frequency band and each sample contains information about the targets. The use of such a narrow pulse also has a second substantial advantage for the detection and identification of shallow targets, in that the transmitted pulse magnitude has fallen to a low value before the pulse reflected from the target returns to the antenna. This "time isolation" effectively minimizes the width of the radar "dead zone" and enables the scattered pulse to be observed over a wide time span. A second form of isolation exists in the choice of the antenna system. The pulse radar uses a pair of crossed, loaded, folded dipoles with 0.6m (2 feet) long arms lying flush with the ground surface (see Figure 1). The crossed-dipole antenna system achieves substantial isolation between transmit and receive antennas. For a perfectly orthogonal pair and no target perturbation, the transmitted pulse would not be observed on the receive antenna. In practice, antenna isolation on the order of 60 dB below the nominal pulser voltage is achieved routinely. Such isolation further minimizes the width of the "dead zone" and is essential for shallow-depth target identification. The dipoles are heavily loaded, with both resistors and incorporated absorber in the antenna to reduce multiple reflections and consequently reduce pulse distortion caused by the antenna. The crossed-dipole antenna system has two additional advantages for the identification of subsurface targets. First, being a cross-polarized system it is insensitive to reflections from layers which are parallel to the antenna arms. An important example is the ground surface whose reflection of the incident pulse energy would produce extraneous signals in other non-orthogonal systems. Second, received waveforms obtained from objects which have no symmetry with respect to the antenna arms go through a polarity reversal as the crossed-dipole antenna system is rotated (about its vertical axis) by 90°. This feature represents a valid method by which a target can be separated from an extended no-target echo which is introduced by multiple reflections on the antenna structure[3].

Typical raw time-domain waveforms received with the antenna oriented at 0° and at 90° over the center of a plastic mine-like target are shown in Figure 3. Several waveform features can be described. The first sharp impulsive-type portion of the waveform is due to direct coupling between the transmit and receive antennas. From the amplitude of the coupling signal and the pulser output, it

*A smaller antenna (0.15 m) is later used for a more specific purpose of mine identification.
Figure 3. Typical raw waveform received by the pulse radar system.
is seen that about 60 dB isolation is achieved. Note that this signal does not change significantly with antenna orientation and thus can be removed by forming the difference of the two waveforms. The coupling signal is a source of clutter but it is also useful as a time reference for target depth and range, since it occurs at essentially the same time the source impulse is radiated from the feed terminals of the transmit antenna. The next feature of the waveform beyond the impulse is the random clutter due to the ground surface irregularities directly beneath the antenna. Because of the short duration of the impulse and good antenna design, this clutter feature dies out in a few nanoseconds. Thus, only a small portion of the clutter overlaps the return from the mine-like target. The signal from the mine-like target appears to be rather strong. Furthermore, it reverses polarity when the antenna is rotated by 90°, thus, its amplitude will double in the difference waveform. The mine-like target signal extends through a time window of approximately 30 ns and falls to a negligible level at the time the balun reflection occurs. The balun is necessary for connecting the unbalanced impulse generator to the balanced dipole antenna. The impedance mismatch at this connection is the source of the balun reflection. The balun reflection limits the width of the reflectionless time window of the system. In the present system, the width of the reflectionless time window is 36.5 ns, which turned out to be wide enough for the identification of the shallow subsurface targets considered in this study. For a wider window, one can lengthen the delay cable at the balun-antenna connection. One can also greatly suppress the effects of the balun reflection by shortening the length of the delay cable at the balun-antenna connection. In this case, the balun reflection would occur in the time region where the target signal is much higher in amplitude. In a later section, we describe a smaller antenna which was used for improved target identification performance. This small antenna was built with the delay cable shortened and the balun structure placed almost at the antenna feed points. The balun reflection can be completely eliminated if a balanced pulser is made available in the future. Elimination of the balun would also yield a narrower transmitted pulse due to less cable loss and dispersion.

An unprocessed time-domain waveform is present in the receiver for target characterization and identification. The structure of the receiver basically consists of a sampling oscilloscope for signal reception, a signal-processing unit for clutter and noise reduction, and a unit for target characterization and identification. In this study, because of the flexibility it offered, a general-purpose digital computer was first used to control the sampling oscilloscope and to implement the processing, characterization and identification units. After all of the target characterization and identification procedures had been established, much of the flexibility was discarded and a relatively simple system designed for target detection and identification. Such a system was implemented with a microcomputer for target identification in real time. Discussion of the microcomputer system is presented in Chapter VIII.
C. The Subsurface Targets

Five targets of similar size were buried at the same depth of 5 cm (2 inches, measured from the ground surface to the nearest target surface). Figure 4 shows the geometry of the targets.

All targets were buried in the backyard of the ElectroScience Laboratory at points where the ground is known to be relatively undisturbed (i.e., free of other objects). The average dc conductivity within 30 cm (12 inches) of the ground surface measured at the target sites ranged from 30 mS/m for wet ground to about 20 mS/m for dry ground and 10 mS/m for icy ground. The relative dielectric constant measured at approximately 100 MHz ranged from 25 for wet ground to 16 for dry ground and 9 for icy ground.

Since a goal of this study was to achieve separation of a mine-like target from other (false) targets using radar data, a major effort was directed toward the study of the mine-like target. The method of identification developed here can easily be adapted to systems in which other targets are considered as desired targets or targets to be separated.

Backscattered waveforms were obtained using the subsurface pulse radar system. Measurements were made at different ground locations with respect to the various targets. Locations of the antenna center for these measurements are shown as dots in Figure 5. At each location two backscattered waveforms were obtained using two different antenna orientations, one of which was a 90° rotation with respect to the other. A standard antenna orientation used in obtaining the measurements is shown in Figure 5. Measurements were obtained with the antenna center vertically above the center and edges of the targets. Beyond the target edges, measurements were made at the regular interval of 15 cm (6 inches).

Data accumulation was started in early June 1977 and continued through early April 1979. During this period the ground condition changed from wet to dry and to icy. Data were obtained for each ground condition to gauge the effects of the changing ground condition on the characterization and identification of the subsurface targets.
Figure 4. Physical characteristics of the subsurface targets.
Figure 5. Measurement locations and antenna orientation.
D. Raw Measured Waveforms

All waveforms collected by the Terrascan-like radar used in this study consist of 256 samples in a time window of 50 ns. The (hardware) basic sampling period $T_b$ is 0.2 ns, giving a sampling frequency of 5.12 GHz*.

There are three possible classes of signals present in these raw waveforms.

1. **Noise:** noise refers to extraneous signals which are not in any way related to the radar source signal. Examples are thermal noise, interference, etc.

2. **Clutter:** clutter refers to extraneous signals which are related to the radar source. Examples are transmit-receive coupling, reflection from ground surface irregularities, and echoes from objects other than the desired target.

3. **Desired Signal:** desired signal refers to echoes of the incident source energy from the desired target.

For shallow targets the desired signal may include direct reflections from the target and multiple reflections between the target and the antenna. Since the antenna is so near the target, the antenna radiation mechanisms and the target scattering mechanisms may not be distinct.

Noise and clutter are the extraneous signals that the signal-processing unit is designed to suppress under certain conditions.

The scattered fields from the targets, both desired and undesired, plus noise and clutter produce a signal at the terminals of the receive antenna. In most conventional receivers noise is reduced by the introduction of filters. For broad-band signals this is not possible but noise is reduced substantially by averaging a number of received waveforms. In general, however, for this antenna system even in our local urban environment where many strong interfering signals exist, the voltage pulse caused by the scatterer is clearly visible on the oscilloscope. In the subsurface pulse radar system, due to the low sensitivity of the antenna system to above-

*Waveforms collected by the microcomputer system consist of 128 samples in a time window of 25 ns. The microcomputer system is discussed in Chapter VIII.
ground disturbances, the noise level is inherently low. Furthermore, it was found that a simple arithmetic averaging process is an effective means for reducing noise[22,24]. This means of course that the noise is not target-induced.

Typical average raw waveforms are shown in Figure 6. The second waveform (---) in each figure is obtained by rotating the antenna by 90°. If the observed signal is caused by direct coupling between the transmit and receive antenna (T-R coupling), the signal would not be changed by this rotation. On the other hand if the signal is caused by any external scatterer, a polarity reversal is observed. These raw waveforms illustrate the various classes of signals. Figure 6-a shows a no-target waveform which is a received waveform with no target (desired or undesired) present within the radar range. Such a waveform, after averaging, contains clutter only. Figure 6-b shows a waveform from the desired mine-like target. In this waveform, the T-R coupling and the ground surface clutter occur early in time and because of the shallow target depth a certain portion of the desired signal is overlapped by the clutter. It is these extraneous signals that various signal-processing techniques are designed to suppress. Figure 6-c shows a waveform from the brass cylinder.

E. Processed Waveforms

Before proceeding to the target identification algorithms, a certain amount of preprocessing of the data is desirable. This is essential here since the goal is to obtain the purest scattering data possible for target characterization. These steps are made possible by the availability of a computer in the measuring system. The data processing will not all be essential in a field system to detect and identify such targets. It is envisioned that any such preprocessing that may be required can be done in a microcomputer which will be a part of the final system. The preprocessing here included:

1. **Arithmetic averaging**: this process forms the arithmetic average of ten raw waveforms at the same antenna location and orientation.

2. **Amplitude shift**: any dc drift in the waveforms is corrected by adjusting the base line.

3. **Gating**: the time regions before the T-R antenna coupling and after the first balun reflection are replaced by a straight line at zero level. The resulting "effective" time window (same for all waveforms) is 36.5 ns wide (186 samples).

4. **Time shift**: the effective time window is shifted to the same time region for all waveforms.
Figure 6. Typical average raw waveforms from the subsurface targets.
5. 90°-rotation difference technique: this process forms the difference between two average, shifted and gated waveforms from the same antenna location but with different antenna orientations of which one is 90° rotation with respect to the other.

6. Multistation averaging: this process forms the arithmetic average of all the difference waveforms (5. above) from the antenna locations which present identical relative geometry between antenna and target.

These processed waveforms are considered to be relatively noise and clutter-free. Furthermore, they contain only the back-scattered information from the individual targets since the ground of the target sites was undisturbed (free of other objects) and relatively smooth. These processed waveforms are to be used only to establish the parameters of identification system. They are not used for the identification of an unknown target.

A set of processed waveforms and their Fast Fourier Transforms (FFT) [64] for the mine-like target at various antenna locations in a wet ground is shown in Figures 7 and 8. Typical waveforms for the other targets are shown in Figures 9 and 10.

The following important generalizations with regard to these waveforms are made:

1. All time-domain waveforms exhibit transient behavior in the late-time region where only the natural response of the target exists. This transient behavior is of prime importance, and, as will be shown in Chapter III, dictates the characterization and identification method for these targets.

2. The strong peaks in the FFT's of the waveforms indicate the possible existence of resonance behavior in the back-scattered waveforms. These peaks may be a good approximate measure of the imaginary parts of the complex resonances of the targets in situ. Note that while the time-domain waveforms from different antenna locations over the mine-like target change noticeably, the locations of the strong peaks in their FFT's stay relatively unchanged (see the vertical dotted lines in Figure 8), indicating the complex natural resonances of the target are excitation invariant. This was anticipated and is the most attractive feature of the target characterization scheme.
ANTENNA LOCATION - CENTER

15 cm EAST OF CENTER

15 cm SOUTH OF CENTER

15 cm WEST OF CENTER

15 cm NORTH OF CENTER

Figure 7. Processed waveforms from the mine-like target at different antenna locations in wet ground.
Figure 8. FFT of the processed waveforms from the mine-like target.
Figure 9. Processed waveforms from the other subsurface targets.
Figure 10. FFT of the processed waveforms from the other subsurface targets.
3. For the waveforms given in Figures 7 and 9 the signal level of the cylinder is the highest while the signal level of the sphere is the lowest. As a reasonable quantitative parameter for comparison of signal and clutter levels, the following definition of signal-to-clutter ratio (S/C) was used in this study.

\[
S/C = \frac{E_T}{\bar{E}_{NT}} = \frac{E_M - \bar{E}_{NT}}{\bar{E}_{NT} - \bar{E}_{NT}}
\tag{1}
\]

where

- \(E_T\) is the energy of the target signal,
- \(E_M\) is the energy of the measured waveform, and
- \(\bar{E}_{NT}\) is the statistical mean energy of the ensemble of clutter or no-target waveforms used to estimate \(E_{NT}\). In this study, we considered only single-target situations, hence a collection of 51 no-target measurements taken at various locations in the vicinity of the target site was used as the ensemble of clutter waveforms.

The Energy of a waveform was defined and estimated as follows.

\[
E = \frac{\int_{t_s}^{t_e} r^2(t) \, dt}{(t_e - t_s)/T_B} \tag{2}
\]

where \(r(t)\) is the waveform under consideration and \(t_s, t_e\) are the start and stop-time of the interval of interest. In this study \(t_s\) was taken to be the time at which the absolute maximum of the waveform occurred and \(t_e\) was taken to be the time at which the balun reflection occurred. The reasons for these choices of \(t_s\) and \(t_e\) are given in later chapters.

The mean clutter level was evaluated as

\[
\bar{E}_{NT} = \frac{\sum_{i=1}^{51} \sum_{t_s}^{t_e} \left( \frac{r^2(t)}{(t_e - t_s)/T_B} \right)}{51}
\tag{3}
\]

where \(r_{NT}(t)\) is the \(i\)th no-target waveform in the ensemble and \(t_s, t_e\) are the start and stop time, respectively of the \(i\)th no-target waveform.
Using the above definitions, the signal-to-clutter ratio at various antenna locations over the 5cm deep targets were evaluated and are given in Figure 11. It was found that the signal-to-clutter ratio for the mine-like target ranged from 0.21 to 3.50 depending on the antenna location and orientation*. The brass cylinder and the wood board targets had the highest and lowest signal-to-clutter ratios, respectively.

The three items mentioned above: the transient behavior, the complex natural resonances and the signal level of the backscattered waveforms are of prime importance in subsurface target identification. Their dependence on changing ground conditions complicates the identification process. Any practical subsurface target identification algorithm must be able to adapt to this changing condition and identify the desired target in a wide range of, if not all, ground conditions. A comparison between the brass cylinder waveform in dry and icy ground given in Figure 12 clearly shows the effects of changing ground condition. Although both waveforms exhibit similar transient behavior, the time intervals between the zero crossings are different, indicating a shift in the locations of the target resonances. The amplitudes of the two waveforms are also different.

The FFT's of the backscattered waveforms indicate that the strongest frequency concentration is at about 70 MHz, furthermore, almost all signal energy is in the 0-500 MHz frequency band. This "system bandwidth" is of great significance in subsurface target identification for it dictates the number of target resonances and the magnitude of the corresponding residues in the backscattered waveforms.

In the next chapter we attempt to characterize the various subsurface targets by approximating their processed backscattered waveforms with a finite complex exponential series with the complex exponents being the complex natural resonances of the targets. A method for extracting these resonances directly from the time-domain waveforms will be presented. Results from the application of this method are given.

*S/C depends also on the ground condition. The estimates given in Figure 11 was based on a set of measurements obtained in a relatively dry ground condition over a time period of several days. Furthermore, S/C at symmetric locations are assumed equal. S/C = 0 when E_M = E_NT.
Figure 11. Signal-to-clutter ratio estimates of the waveforms from the subsurface targets at different antenna locations.
Figure 12. Processed waveforms from the brass cylinder in dry and icy ground.
CHAPTER III
CHARACTERIZATION OF SUBSURFACE TARGETS BY THEIR COMPLEX NATURAL RESONANCES

A. Objectives

This chapter summarize a study of the characterization of subsurface targets by their complex natural resonances. A method for extracting the resonances from the processed backscattered waveforms is derived for completeness. The method is known as Prony's method [12-15] and, when applied to measured data, it is extremely sensitive to the values of its parameters. An approach to solve certain of these problems will be presented. Prony's method is applied to the processed backscattered waveforms and an analysis of the resulting resonances is focused on the following:

1. The excitation invariance of the complex natural resonances of the individual targets with respect to antenna location.

2. The degree of distinction between the complex natural resonances of the different targets.

3. The effects of changing ground condition on the location of the complex natural resonances.

B. Complex Natural Resonances

The concept of using complex natural resonances for target characterization is developed from the fact that all finite-size objects have resonances that depend on their physical characteristics such as size, shape and composition as well as the medium surrounding the object. These resonances, however, are independent of the excitation[40]. As a useful but inexact analogy, in circuit theory, the form of the transient response of a lumped linear circuit may be determined from the knowledge of the resonances and the corresponding residues of the response function in the complex frequency plane. The actual transient response of the circuit is then simply a summation of all the residues multiplied by the inverse transforms of the resonances. In 1965, Kennaugh and Moffatt[41] generalized the impulse response concept to include the distributed parameter scattering problems and suggested that a lumped circuit representation, at low
frequencies or long time, was possible. Later, similar and more formal representations have been designated as the Singularity Expansion Method (SEM)[7-8]. This hypothesis is generally supported by the fact that typical transient response waveforms, such as those shown in Chapter II, appear to be dominated by a few exponentially damped sinusoids. Based on this concept, a subsurface target can be characterized by a set of complex natural resonances which is independent of the location and orientation of the crossed-dipole antenna. These resonances, however, are dependent on ground condition. Such a characterization is attractive for it catalogs a target by a small set of complex numbers.

The backscattered waveforms from the subsurface targets received by the pulse radar system are good approximations to the impulse responses of the targets. Furthermore, they appear to be dominated by a few exponentially damped sinusoids, and thus can be represented as

\[ r(t) = \sum_{n=1}^{N} a_i e^{s_i t} \]

(4)

where \( r(t) \) is the received transient waveform, \( s_i \) 's are the complex resonant frequencies or pole locations in the complex frequency plane. These have, by common usage in this representation, become designated as complex resonances or more simply as resonances. These various terms will be used for \( s_i \) in this document. \( a_i \) 's are the corresponding residues and \( N \) is the number of complex resonances within the frequency band of the radar system. The corresponding expression in the complex frequency domain is

\[ \mathcal{L}[r(t)] = \sum_{i=1}^{N} \frac{a_i}{s - s_i} \]

(5)

where \( \mathcal{L}[\cdot] \) is the Laplace transform operator[42] and \( s \) is the complex frequency. Note that the resonances are not dependent on antenna location and orientation however, the residues are.

In order to exploit Equation (4), it is necessary to first determine the values of the complex natural resonances of the targets. The method used here extracts the resonances of a target directly from its transient response. This method is known as Prony's method, which was first derived by Prony in 1795[12], and was later suggested by Van Blaricum, et al., for extracting the pole singularities of transient waveforms in 1975[14].
C. **Derivation of Prony's Method**

In discrete form, Equation (4) can be written as

$$ r(KT_B) = \sum_{i=1}^{N} a_i e^{s_i KTB}, \quad K = 0,1,2,\ldots $$

(6)

where $K$ is the sampling index and $T_B$ is the basic hardware sampling period of our measurement system (see Chapter II). For an exact solution of the $2N$ unknowns $a_i$ and $s_i$, we can set up $2N$ (nonlinear) equations by using $2N$ sample values of $r(KT_B)$. Prony's method uses $2N$ uniform samples, and

$$ r(nT) = \sum_{i=1}^{N} a_i e^{s_i nT} \quad ; \quad n = 0,1,2,\ldots, M = 2N-1 $$

(7)

where $T$, the Prony interval, is the interval between the samples used along the waveform. In general, $N$ itself also represents an unknown which is usually fixed by a trial and error process.* If no waveform interpolation is exercised, $T$ is equal to integer multiples of $T_B$.

Writing out Equation (7), we have $2N$ equations

$$
\begin{align*}
    r_0 &= a_1 + a_2 + \cdots + a_N \\
    r_1 &= a_1 z_1 + a_2 z_2 + \cdots + a_N z_N \\
    r_2 &= a_1 z_1^2 + a_2 z_2^2 + \cdots + a_N z_N^2 \\
    \vdots \\
    r_M &= a_1 z_1^M + a_2 z_2^M + \cdots + a_N z_N^M
\end{align*}
$$

(8)

where

$$ r_n = r(nT) $$

and

$$ z_j = e^{s_i T}. $$

* $N$ represents the number of target resonances which are excited by interrogating frequencies within the "system bandwidth".
Equation (8) is a set of nonlinear equations in the \( z_i \)'s. Let \( z_1, z_2, \ldots, z_N \) be the roots of the algebraic equation

\[
\alpha_0 + \alpha_1 z^1 + \alpha_2 z^2 + \cdots + \alpha_N z^N = 0
\]

so that the left hand side of Equation (9) is equal to the product

\[
(z-z_1)(z-z_2) \cdots (z-z_N) = 0
\]

that is,

\[
\sum_{m=0}^{N} \gamma_m z^m = \prod_{i=1}^{N} (z-z_i) = 0
\]

Thus, if we can evaluate \( \gamma_m \), then \( z_i \) can be obtained by a simple factorization of an Nth degree polynomial. To solve for \( \gamma_m \), we obtain from Equations (7) and (8)

\[
\sum_{m=0}^{N} \gamma_m z^{K+m} = \sum_{m=0}^{N} \gamma_m \left( \sum_{i=1}^{N} \alpha_i z^{K+i} \right) ; K = 0,1,2,\ldots,M-N
\]

Interchanging the order of the summation yields

\[
\sum_{m=0}^{N} \gamma_m z^{K+m} = \sum_{i=1}^{N} \alpha_i z^i \left( \sum_{m=0}^{N} \gamma_m z^m \right)
\]

From Equation (11), we see that the summation inside the parenthesis of the above equation is zero, thus, we arrive at the desired linear homogeneous difference equation

\[
\sum_{m=0}^{N} \gamma_m K^{m} = 0 ; K = 0,1,2,\ldots,M-N
\]

Thus, the sample values of \( r(t) \) satisfy an Nth order linear homogeneous difference equation. This difference equation is commonly referred to as the Prony difference equation.

The Prony difference equation is linear and homogeneous, and can be used to solve for the \( N+1 \) coefficients, i.e., \( \gamma_m \)'s. In the classical Prony's method, these coefficients are obtained by setting \( \gamma_N = 1 \) and solving the resulting matrix equation by matrix inversion that is,
\[ AB = C \]

where

\[
A = \begin{bmatrix}
    r_0 & r_1 & r_2 & \cdots & r_{N-1} \\
    r_1 & r_2 & r_3 & \cdots & r_N \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    r_{M-N} & r_{M-N+1} & r_{M-N+2} & \cdots & r_{M-1}
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
    z_0 \\
    z_1 \\
    \vdots \\
    z_{N-1}
\end{bmatrix}
\]

and

\[
C = \begin{bmatrix}
    r_N \\
    r_{N+1} \\
    \vdots \\
    r_M
\end{bmatrix}
\]

Note that for \( M = 2N-1 \), \( A \) is a square symmetric circulant matrix and is readily invertible. Standard computer routines such as GELG[43] can be used to do the matrix inversion. Once the \( r_m \)'s are determined, the next step is to solve for the \( N \) values of \( z_i \). These \( z_i \)'s are obtained by finding the roots of Equation (11). The \( N \) roots are complex numbers and because \( r(t) \) is real, these complex numbers appear in complex conjugate pairs. The polynomial root finding process can be easily performed by using standard routines such as Muller[44,45].

It is now trivial to obtain the poles \( s_i \). Since the roots of Equation (11) were defined by Equation (8), the poles are simply

\[
s_i = \frac{1}{T} \ \gamma_n(z_i)
\]

(14)

The final step in Prony's method is to determine the value of the residues \( a_i \). To do this, we simply solve the matrix equation embodied in Equation (8). In matrix form this set of equations is written as

\[
DE = F
\]

(15)

where
The above derivation of Prony's method is valid only when all natural resonances present are simple poles. For multiple-order poles, a slight modification is necessary in solving for the residues. The derivation of Prony's method for multiple-order poles is given in Appendix A for completeness. However, in this study we have not found it necessary to postulate multiple-order poles.

In summary, Prony's method solves for the complex natural resonances (poles) and the corresponding residues associated with the backscattered time-domain waveforms from a system of nonlinear equations (Equation (8)) by breaking it down into three simple steps:

1. Solve for the values of $a_m$'s of the linear Equation (13) by matrix inversion.

2. Solve for the poles by factoring the polynomial of Equation (11).

3. Solve for the residues from the linear Equation (15) by matrix inversion.

The derivation of Prony's method is simple enough. However, its application to the measured backscattered waveforms is a much more complicated process. The following section outlines some of the difficulties.
D. Clutter and/or Noise in Prony's Method

Prony's method has been found to be extremely sensitive to clutter and/or noise. Its ability to extract the complex natural resonances of a waveform accurately is severely inhibited by the presence of clutter and noise [46-48]. Since Prony's method is an interpolation process (otherwise referred to as curve fitting), in the presence of clutter and/or noise, it will give a set of poles which fit the noisy transient response but will not necessarily represent the complex natural resonances of the target. Various signal-processing techniques have been applied to reduce the effect of clutter and/or noise in Prony's method [46-48], with the most commonly used being the least-square error technique. With it, Equation (13) in the previous section is solved in the least-square sense. In this case, M samples are used in lieu of 2N samples where M>2N. Thus, the matrix A becomes rectangular, and Equation (13) is solved by the pseudo-inverse technique

\[ A^T A = A^T C \]  
\[ \phi B = D \]  

where
\[ \phi = A^T A \]
and
\[ D = A^T C \]

Since \( \phi \) is the signal covariance matrix, it is real, symmetric and positive definite, and is thus readily invertible to yield the value of \( \eta_{m} \)’s.

A second technique applied to reduce noise in Prony's method was brought about by the observation that, in solving for the N+1 \( \eta_{m} \)'s in the M homogeneous Equations (13), we can, instead of setting \( \eta_{N} = 1 \), require that the Euclidean norm of the \( \eta \) vector be 1, i.e.,

\[ \sum_{m=0}^{N} \eta_{m}^2 = 1 \]

Such an approach leads to the eigenvalue method [48,49,52].
Instead of setting the leading coefficient \( a_1 \), we can of course set any of the \( N+1 \) coefficients to 1 in solving for the \( a_m \)'s of Equation (10). Such a constraint leads to the interpolation version of Prony's method\[51,52\].

The classical Prony's method, the eigenvalue method and the interpolation version of Prony's method were all considered in this study. For completeness, derivations of the eigenvalue method and the interpolation version of Prony's method are given in Appendix B.

Numerous other signal-processing techniques have been applied \[46-47\], thus far, however, no completely satisfactory result has been reported using measured data. In the following section a systematic procedure that is giving good results for the present data is outlined. This procedure was used in extracting the complex natural resonances of the processed backscattered waveforms in Chapter II and yielded our best results to date. As we will see, the procedure does indeed provide satisfactory target separation.

The problem is really one of linear prediction and is prominent in many diverse disciplines\[53\]. No general solution has yet emerged and the acceptability of a given method really depends upon the application. It is interesting however that minimizing the total squared error (actual vs estimate) in some sense is a common starting point. Yet this in no way optimizes the resonance locations. For our purpose because the resonance locations need not be found in real time, present methods are adequate if not completely satisfying. A real need is to compile and translate all of the various methods already being used. Such a tutorial unified review would be invaluable but is beyond the scope of the present effort. We can of course easily incorporate any new techniques into the identification scheme.

E. Applying Prony's Method to the Processed Measured Backscattered Waveforms

In applying Prony's method, one approach is to pre-determine the following parameters:

1. \( N \), the number of poles to be extracted from the waveform. Van Blaricum\[14,15,47\] suggested a method which relies on the fact that the \((N+1)\)th eigenvalue of the matrix should equal \( \sigma^2 \), the variance of the additive gaussian stationary and uncorrelated noise. Such a method does not seem practical for our measured data in which the clutter seems to be nonstationary (transient).

2. \( T \), the Prony interval. Obviously, undersampling (\( T \) too large) will almost surely bring aliased results. It was also found that oversampling produces extraneous high frequency poles.
3. \( t_s, t_e \) the start and stop time of the fitting interval. 
\( t_s \) must lie in the time region where the forced response portion of the backscattered waveform has ended and \( t_e \) must lie in the region where clutter/noise effects are not dominant.

4. \( M \), the number of sample points used in the fitting process. 
\( M \) determines the amount of overspecification on the system of Equations (13).

In the presence of clutter and/or noise, it was found that the accuracy of the extracted resonances was found to be extremely sensitive to the values of the above five parameters[48]. For the method to yield an accurate solution, we have to find the "right" set of values for these parameters. The approach developed in this study is to vary these parameters (over a reasonable range) and assume that the "right" values of the parameters corresponding to the "desired" resonances are those that allow the closest approximation to the measured waveform in the time domain. That is, a calculated waveform is developed from the resonances and residues found, and this waveform is compared to the original waveform point by point over the fitting interval \([t_s, t_e]\) and the total squared error found. The solution which affords the smallest total squared error is considered to be the "desired" solution. This approach is used to find the coefficients of the difference equation but once done for a target needs not be repeated for target-separation purposes. It is conceivable that such a searching procedure can be lengthy. Furthermore, ranges of the parameters are dependent on the waveform being processed. However, with a little experience, one can usually minimize them. The ranges of these parameters in this study were fixed as follows:

1. The number of "significant" peaks in the Fast Fourier Transform of the waveforms is usually a good measure of \( N \) and since the number of "significant" peaks is between 2 and 7 in all waveforms considered, the range of \( N \) was chosen to be from 4 to 14 (we assumed that one peak corresponded to at most two poles).

2. Shannon's sampling theorem constrains the maximum value of \( T \), while the bandwidth of the radar system (<500 MHz) constrains the minimum value of \( T \).* The values of \( T \) were chosen to be 3\( T_B \), 5\( T_B \), ..., 10\( T_B \) corresponding to minimum and maximum Nyquist frequencies of 256 MHz and 768 MHz, respectively.

*Frequencies beyond the system bandwidth contains noise only unless we attempt some spectral estimation techniques. The approach may be worthy of study when studying "deeper" targets.
3. The values of \( t_s \) were chosen to be \( t_{\text{max}}, (t_{\text{max}} + 2T_B), (t_{\text{max}} + 4T_B), \ldots (t_{\text{max}} + 8T_B) \) where \( t_{\text{max}} \) is the time at which the absolute maximum of the waveform occurs. It was found that such a choice ensured a decaying nature in almost all the waveforms considered. \( t_e \) was chosen to be the time at which the balun reflection occurs (see Chapter II).

4. Since a vastly oversized \( M \) would result in an unstable solution from Prony's method\(^{13,15,48}\), the values of \( M \) were chosen to be \( 2N, 3N, \ldots 6N \).

Each set of values of the five parameters \((N,T,t_s,t_e,M)\) will give a set of complex resonances when Prony's method is applied to a waveform. This set of complex resonances maximizes the fit between the approximated waveform \( r_A(t) \) and the measured waveform \( r(t) \) in the interval \([t_s, t_s + (M-1)T] \) with the sampling interval of \( T \). For all complex resonances resulting from all possible sets of \((N,T,t_s,t_e,M)\) in the chosen range, the "desired" set of complex resonances is chosen to be the one which minimizes the total normalized point-by-point squared error \( e \) over the error-calculating interval. The error \( e \), which will be henceforth referred to as mean-square error, is defined as

\[
e(t) = \left( \sum_{t} (r(t) - r_A(t))^2 \right) / \left( \sum_{t} (r^2(t) + r_A^2(t)) \right) \quad t = 1T_B . \tag{19}
\]

In this study, \( r(t) \) was taken to be the processed measured waveform and the approximated waveform \( r_A(t) \) was generated via the method of linear prediction\(^{53}\), where

\[
r_A(t + m_0 T) = \sum_{m=0}^{N} \frac{-i^{m}}{m!m_0} r_M(t + mT) . \tag{20}
\]

In Equation (20), \( r_A(t) \) and \( r_M(t) \) are the approximated and the processed measured waveform, respectively, the \( m_0 \)'s are the difference equation coefficients obtained from the Prony's method, and \( m_0 \) is an index chosen for suppression of clutter and noise effects. In this study, \( m_0 \) was chosen to be the coefficient of maximum magnitude. With Equation (20), the mean-square error \( e \) can be expressed as
From Equations (12) and (21), we note that the mean-square error is zero when the measured waveform is free of clutter/noise and is perfectly characterized by Equation (4). The error should be small when \( r_M(t) \) is closely approximated by Equation (4).

The choice of the above error criterion is related to the form of the correlation coefficient \( \varphi \) used in the target identification algorithm of Chapter IV, in such a way that minimization of \( \varphi \) results in the maximization of the correlation coefficient.

With the above search procedure, Prony's method and its variations were applied to the processed waveforms to extract their complex natural resonances. Results are shown in the next section.

F. The Extracted Resonances of the Subsurface Targets

The locations of extracted resonances of the mine-like target at different antenna locations in icy ground are plotted in Figure 13 (here only poles in the upper left half of the plane are shown, details are given in Appendix C). From Figure 13, we make the following observations:

1. The extracted resonances tend to form "clusters". Some possible clusters are shown in Figure 13. The formation of these clusters is based on the obviousness of clustering of the resonances and the known fact that the accuracy in determining the real part of the extracted resonance is normally poor. A cluster can contain at most one pole extracted from a waveform. Poles with residues which are three orders down in magnitude compared to the maximum residue are discarded. Poles which are remote from the clustered groups are excluded. Beyond an obvious weighing dictated by the actual pole locations no real significance should be attached to the shape of the closed contour surrounding each cluster.

2. Only a small number of clusters or resonances are present.
Figure 13. Location of the extracted resonances of the mine-like target at different antenna locations in icy ground.
3. The variation in the real parts of the resonances within a cluster is generally greater than the variation in their imaginary parts. There is at least one more major factor, besides the ever-present clutter/noise, that causes such variations, namely, the target-antenna interactions. At the shallow depth of 5 cm, for most antenna locations considered, the targets are in the near field of the antennas for the entire bandwidth (< 500 MHz) of our radar system.

4. An additional factor contributes to the variations in the extracted resonances from the mine-like target, namely, its complex structure. This target possesses the most complex structure of all targets considered.

5. The phenomenon of certain resonance(s) being weakly excited in certain radar aspects is evident. The weakly excited resonances were not extracted.

6. As expected, the residues are aspect dependent. This becomes evident by noting the variations of the magnitude of the residues of the poles in the clusters (see Appendix C).

7. The mean-square error $\varepsilon$ is small ($< .01$, see Appendix C) in all cases considered, meaning that the finite sum of complex exponentials fits the measured waveforms well. This is a necessary condition for our identification algorithm whose correlation coefficient is defined to be unity minus the mean-square error $\varepsilon$.

In this study, a subsurface target was characterized by the set of average extracted resonances. Averaging was performed over all the extracted resonances in each cluster. For the mine-like target, the average extracted resonances are shown as solid dots in Figure 13. Parameters such as the variation from the average of each pole within the cluster is not meaningful because of its causes which include, besides the effects of clutter and noise, the possible variations in the pole excitation at the various antenna locations and orientations. Slight pole variations due to the variations in the antenna locations and orientations is possible for the finite exponential sum representation of the target's transient response is only an approximation and that the targets considered are located in the closed vicinity of the radar system.

The extracted resonances shown in Figure 13 were obtained using classical Prony's method (i.e., $\alpha_i=1$). Classical Prony's method was found to extract poles with tighter clusterings among the results given by other methods under the constraint $\alpha_m=1, m=0, 1, \ldots, N[52]$. The eigenvalue method provided results similar to those given by the
Classical Prony's method. Thus, no clear cut choice of method was
discernable. Accordingly, the extracted resonances shown in this
dissertation were the results of either of these two methods.

In order to see the effects of the changing ground condition on
the location of the extracted resonances, the average resonances of
the mine-like target in different ground conditions are tabulated in
Table 1 and are plotted in Figure 14. From Figure 14, we see that
there were five (pairs) extracted resonances. The imaginary parts of
the extracted resonances were relatively insensitive to changes in
ground condition. This seems to imply the resonances of the mine-
like target are internal resonances. This also means that the target
identification scheme when applied to this target will be relatively
insensitive to ground conditions.

The implications of the fact that there were five (pairs) reson-
ances extracted from the mine-like target waveforms is significant.
It means that this target can now be characterized by a finite-order
system.

Not all the extracted resonances are related to the scattering
mechanisms of the mine-like target. In fact, the lowest resonance
was found to be the antenna resonance of the system. This becomes
particularly clear when we study the resonances extracted from the
mine-like target waveforms collected with a 12m long antenna. By
gating out the late-time portion of the backscattered waveform from
the mine-like target received by the 12m long antenna, we effectively
eliminated the resonance of the antenna created by the finite length
of the antenna arms. Thus, poles extracted from these waveforms are
all target-related. A typical such backscattered waveform in the
time domain is shown in Figure 15. The short time window (compared
to the 0.6m long antenna waveforms of Figures 7) of the waveform
indicates the absence of any low frequency content. The average
extracted resonances from the mine-like target waveforms received by
the 12m long antenna at various locations are shown in Figure 16.
A quick comparison with the extracted resonances from the 0.6m long
antenna waveforms reveals the fact that the resonance with imaginary
part of approximately 60 MHz is the antenna resonance. Thus, for the
system with the 0.6m long antenna, four (pairs) target resonances
were present in the received waveforms. The antenna resonance was
extracted from almost every waveform of all targets considered.

In contrast to the case of the plastic mine-like target, the
brass cylinder was found to possess external resonances. Table 2
lists the average extracted resonances of the brass cylinder in
various ground conditions. Locations of these resonances are also
plotted in Figure 17. From Figure 17 we see the following effects
of the changing ground condition on the extracted resonances of the
brass cylinder. First, the antenna resonance is insensitive to changes
in the ground condition. This may be attributed to the fact that the
arms of the crossed-dipole antenna were not in electrical contact with the ground surface. Second, the imaginary parts of the three higher-order* resonances increased significantly when the ground changes from dry to icy. This is to be expected, because the resonances of the brass cylinder are external resonances. The increase in the imaginary parts of these external resonances indicated a decrease in the value of the dielectric constant of the ground. Third, the real part of the three higher-order resonances generally decreased as the ground changed from dry to icy, indicating that icy ground in this case was more lossy. The increase in loss seemed to be the reason for the absence of the real cylinder pole in icy ground.

The average extracted resonances of the aluminum sphere, copper sheet and wood board are tabulated in Table 3. From Table 3 we see that the antenna resonance is present in the waveforms of all targets. Note that the extracted resonances of the five targets considered lay in the same general region of the complex frequency plane and are only marginally separated. Such is expected to some extent because all targets considered have (again marginally) similar sizes. Such marginal level of distinction in the poles is expected to present difficult tests for the identification algorithm. Furthermore the number of resonances for the various targets are also close (4 to 5 pairs); this further tests our identification method.

The location of the target resonances are related to the scattering mechanisms of the target. For subsurface targets, these relationships are complicated by the presence of the air-ground interface, the ground condition and the characteristics of the transient antenna system. For shallow targets the near-field effects and the target-antenna interactions further complicate the picture. In this dissertation, we do not intend to explore these relationships. Instead, we proceed to use the extracted resonances for identification of the various subsurface targets. In the next chapter, a basic identification algorithm will be given and identification results using the extracted resonances as the discriminants will be presented.

*Order here denotes increasing imaginary part.
Figure 14. Locations of the average extracted resonances of the mine-like target in different ground conditions.
Figure 15. A typical backscattered waveform received by the 12m long antenna from the mine-like target.
Figure 16. Average extracted resonances from the mine-like target waveforms received by the 12m long antenna.
Figure 17. Average extracted resonances of the brass cylinder in different ground conditions.
**TABLE 1**  
AVERAGE EXTRACTED RESONANCES OF THE MINE-LIKE TARGET IN DIFFERENT GROUND CONDITIONS

<table>
<thead>
<tr>
<th></th>
<th>ICY GROUND</th>
<th></th>
<th>DRY GROUND</th>
<th></th>
<th>WET GROUND</th>
<th></th>
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<tbody>
<tr>
<td></td>
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<td>POLE</td>
<td>POLE</td>
<td>POLE</td>
<td>POLE</td>
</tr>
<tr>
<td></td>
<td>REAL PART*</td>
<td>IMAG PART*</td>
<td>REAL PART</td>
<td>IMAG PART</td>
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</tr>
</tbody>
</table>

*Real and Imaginary parts of the extracted resonances shown in Tables 1, 2 and 3 are in N*per*s and Hz, respectively.*
### Table 2
AVERAGE EXTRACTED RESONANCES OF THE BRASS CYLINDER
IN DIFFERENT GROUND CONDITIONS

<table>
<thead>
<tr>
<th>ICY GROUND</th>
<th>DRY GROUND</th>
<th>WET GROUND</th>
</tr>
</thead>
<tbody>
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<td>POLE IMAG PART</td>
<td>POLE REAL PART</td>
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<tr>
<td>-.1882724E9</td>
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</tr>
</tbody>
</table>

### Table 3
AVERAGE EXTRACTED RESONANCES OF THE ALUMINUM SPHERE,
COPPER SHEET AND THE WOOD BOARD

<table>
<thead>
<tr>
<th>ALUMINUM SPHERE DRY GROUND</th>
<th>COPPER SHEET DRY GROUND</th>
<th>WOOD BOARD WET GROUND</th>
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</thead>
<tbody>
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<td>POLE REAL PART</td>
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CHAPTER IV
THE PREDICTOR-CORRELATOR IDENTIFIER

A. Objectives

This chapter summarizes the target identification procedure based on the predictor-correlator identification method [40,9-11]. A detailed analysis on the predictor-correlator is presented. Identification performances based on real radar measurements are given.

Processing for target identification using the predictor-correlator consists of comparing a measured waveform from an unknown target with a calculated waveform produced using the resonances of a known desired target. The procedure is as follows:

1. Preprocessing: The preprocessor attempts to suppress clutter and noise. For "single-look"* identification, the following preprocessing steps are taken:
   a. Arithmetic Averaging (see Chapter II).
   b. Amplitude Shift (see Chapter II).
   c. Time Shift (see Chapter II).
   d. 90°-rotation Difference (see Chapter II).
   e. Filtering: It was found that with the system under discussion, almost all of the target signal energy resided in the 0-500 MHz region (see Chapter II), thus, to suppress out-of-band clutter and noise a low-pass trapezoidal filter with the transfer function shown in Figure 18 was inserted into the preprocessing unit. Various critical frequencies were tested, the ones shown in Figure 18 yielded the best identification performance.

* i.e., Identification based on a single radar observation
Figure 18. Transfer function of the pre-processor filter used in the 0.6m long antenna system for target identification.

For design flexibility, the filtering processes were performed in the frequency domain with the Fast Fourier Transform (FFT) package available in the digital computer system library. The only goal of the filtering operation is to remove the out-of-band frequency contents without adding any extraneous frequencies to the spectrum of the target response. The trapezoidal filter structure is a digital filter and was used here because of its linear phase characteristics and the availability of the FFT package in the digital computer. The FFT package allows tremendous flexibilities in digital filter design. It is important to note that the use of the trapezoidal filter here was not meant to be "optimum". More extensive study may well yield a better filter structure.

2. Detection: The detector performs a screening operation for the predictor-correlator identifier by rejecting as undesired-target waveforms those waveforms whose parameters are not within the desired ranges. The parameters considered in this study were:
a. Waveform energy (as defined in Chapter II).

b. Peak timing of the waveform.

c. Peak amplitude of the waveform

The desired ranges of the detection parameters were determined by studying the ranges of these parameters of the desired-target waveforms. Examples illustrating the choosing of the detection parameters are given in Section F of this chapter.

3. Prediction: Predict the calculated waveform using the Prony difference equation.

4. Correlation: Calculate the correlation coefficient for threshold identification by comparing the processed and the calculated waveforms. The correlation coefficient is defined to be unity minus the normalized total squared error.

This approach assumes that the poles and the difference equation coefficients for the desired target have previously been obtained. Thus, only simple algebraic operations are involved in calculating the correlation coefficient for an identification decision.

B. The Predictor

The predictor generates the calculated waveform. With the complex natural resonances and a chosen value of $T$, the coefficients $\mu_m$'s of the Prony difference equation (see Equation (12)) can be determined via Equation (11). Thus, for one value of $T$, we can generate a calculated waveform by one of the following methods:

1. One-step prediction:

$$r_C(t+N\delta T, T) = \sum_{m=0}^{N-1} -\mu_m r_M(t+m\delta T)$$

or

2. Interpolation:

$$r_C(t+m_0\delta T, T) = \sum_{m=0}^{N} -\mu_m r_M(t+m\delta T)$$
where

\[ t = t_s + nT_B, \quad n=0,1,2,\ldots \]

and

\[ T = iT_B, \quad i=1,2,\ldots \]

\( r_c(t,T) \) and \( r_M(t,T) \) are the calculated and processed measured waveform, respectively. \( t_s \) is the start-time (see Chapter II and III). The parameter \( m_0 \) is an index chosen for suppression of clutter and noise effects. In this study the interpolation method was used and \( m_0 \) was chosen to be the coefficient of maximum magnitude. By comparing Equations (22), (23) and (12) we note that when the measured waveform is from the desired target, \( r_c(t) \) and \( r_M(t) \) are equal and hence perfectly correlated. Note that one calculated waveform is constructed at each chosen value of \( T \) and the same measured waveform is used to construct calculated waveforms for all chosen values of \( T \).

The one-step prediction method was first used by Hill who applied it to the detection and identification of targets (above ground) near the half space \([40]\). This method was then modified by Moffatt, et al. \([9]\) to become the interpolation method for improved performance in clutter/noise. The predictor uses past values of the measured waveforms only, while the interpolator uses both past and future values and, together with its normalization process, was found to perform better in the presence of clutter/noise.

C. The Correlator

The correlation coefficient, formed by comparing the calculated and the processed measured waveform, is a function of \( T \).

\[
\rho(T) = 1 - \frac{t_s + m_0 T}{t_e - NT + m_0 T} \left( \frac{r_c(t_s, T) - r_M(t)}{t_e - NT + m_0 T} \right)^2
\]

where the start-time \( t_s \) is taken to avoid the forced response of the backscattered waveform while the stop-time \( t_e \) is taken to avoid the low-amplitude signal at the tail end of the waveform. In this study \( t_s \) was taken to be the time the absolute maximum of the waveform occurs, while \( t_e \) was taken to be the time the balun reflection occurs.

Equation (24) can be rewritten as
We note that the numerator of the quotient in Equation (25) is the cross-correlation between the calculated and processed measured waveforms. The nominal range of \( p(T) \) is \(-1 < p(T) < 1\), and

\[
p(T) = 1 \text{ when } r_c(t) = r_M(t) \quad (26)
\]

The quotient term in Equation (24) is identical to the mean-square error \( \mu \) in Equation (21) when the approximated waveform \( r_A(t) \) in the Prony process is equal to the calculated waveform \( r_c(t) \). Thus,

\[
p(T) = 1 - \mu \quad (27)
\]

The importance of Equation (27) lies in the fact that it ties the characterization and the identification processes together such a way that optimization of one process (e.g., minimum \( \mu \)) will lead to the optimization of the other (maximum \( p(T) \)). Therefore, the evaluation of optimum values of the parameters \((N,T,t_s,t_e,M)\) in the characterization process leads also to optimum values in the identification process. This is rather significant in the evaluation of \( \mu(T) \).

From Equations (24) and (25), we see that the interval in the error calculation is from \( t_s+m_0T \) to \( t_e-NT+m_0T \), giving an error interval size of \( t_e-t_s-NT \). Thus, the size of the error interval decreases as \( T \) increases.

D. The Predictor-Correlator as a Filter

In order to understand the operation of the predictor-correlator identifier, it is helpful to consider the identifier as a linear time-invariant filter.

From Equations (21) and (24), we see that, an instantaneous error \( e \) can be defined as
\[ e(t+m_0 T) = r_M(t+m_0 T) - r_c(t+m_0 T) = \sum_{m=0}^{N} \frac{\alpha_m}{\alpha_{m_0}} r_M(t+mT) \quad (28) \]

Thus, the instantaneous error \( e \) can be interpreted as the output of a Finite impulse response (FIR) filter\[54-56\] with the filter coefficients \( \alpha_m \) where

\[ a_m = \frac{\alpha_m}{\alpha_{m_0}} \quad (29) \]

Note that although the filtering operation is based on the sampling interval \( T \), the instantaneous error exists at the sampling period of \( T_B \), where \( T \) is taken to be multiples of \( T_B \). In the \( Z \) domain \[54-56\], the instantaneous error is given by

\[ E(Z) = Z^{-N+m_0} \sum_{k=0}^{k-1} \frac{1}{Z^k} C(Z)R_M(Z) \quad (30) \]

where

- \( E(Z) \) is the \( Z \) transform of the instantaneous error, based on \( T \)
- \( C(Z) = \sum_{m=0}^{N} \frac{\alpha_{N-m}}{\alpha_{m_0}} Z^{-m} \) is the \( Z \) transform of the filter coefficient sequence.
- \( R_M(Z) \) is the \( Z \) transform of the processed measured waveform.

And

\[ T = KT_B, \quad K = 1, 2, \ldots \]

The product \( C(Z)R_M(Z) \) in Equation (30) is the filtering operation in the \( Z \) domain. Since the \( Z \) transform is based on the sampling interval \( T \), thus this product term alone results in samples only at the sampling intervals of \( T_B \) in the time domain. The weighed sum operation (weighed by \( Z^i/k \)) fills the time interval between these samples with samples at finer sampling interval of \( T_B \), and thus assures a better error waveform resolution. The presence of the factor \( Z^{-N+m_0} \) is to make sure that the starting point of the instantaneous error be consistent with that stated in the definition of the instantaneous error for the case of the interpolation method.

Using Equations (11), we rewrite Equation (30) as

\[ E(Z) = \frac{1}{\alpha_{m_0}} Z^{-N+m_0} \sum_{k=0}^{k-1} \frac{1}{Z^k} R_M(Z) \sum_{j=1}^{N} (1-Z^{-1}Z_j) \quad (31) \]
where $Z = e^{s_j T}$ are the locations of the desired-target resonances in the $Z$ plane, $s_j$ are the complex resonances in the $s$ plane and $N$ is the number of complex resonances of the desired target. Note that the locations of the complex resonances in the $Z$ plane are functions of the sampling interval $T$.

From Equations (24-31), we make the following important observations:

1. The mean-square error $\varepsilon$ is the normalized energy of the instantaneous error $e$. $\varepsilon$ is directly related to $e$ as follows.

\[
\varepsilon = \frac{\sum_{t} e^2(t)}{\sum_{t} e^2(t) + 2 \sum_{t} r_M^2(t) - 2 \sum_{t} r_M(t)e(t)}
\]  

(32)

where the summations in Equation (32) are taken over the error interval. The lower and upper bounds of the mean-square error $\varepsilon$ are given by Equation (33)

\[
\frac{1}{1 + \frac{2}{\sqrt{x}} - \frac{2}{\sqrt{x}} ^2} \leq \varepsilon \leq \frac{1}{1 + \frac{2}{\sqrt{x}} + \frac{2}{\sqrt{x}} ^2}
\]

(33)

where

\[
x = \frac{\sum_{t} e^2(t)}{\sum_{t} r_M^2(t)}
\]

and the summations are again taken over the error interval.

The error bounds are plotted as a function of $x$ in Figure 19. From Figure 19, the following observations are made:

a. $\varepsilon$ is bounded as follows:

\[
\varepsilon \leq 0
\]

\[
= 2 \text{ when } e(t) = 2r_M(t) \text{ and }
\]

\[
= 0 \text{ when } e(t) = 0
\]

(34)
Figure 19. Bounds of the mean-square error.
b. The lower bound of c increases monotonically as the energy of the instantaneous error $r'^*$ increases. c approaches 1 as $r'$ approaches infinity.

c. The upper bound of c increases monotonically from 0 to 2 as $r'$ increases from 0 to the value of

$$4\sqrt{r_M^2(t)(((t_e-t_s)/T_B)}$$

At this $r'$ value, c attains its maximum upper bound of 2. The upper bound of c decreases from 2 to 1 as $r'$ increases to infinity. Although the upper bound of r does not increase monotonically as $r'$ increases from 0 through its entire range, the lower bound does. Thus, it is reasonable to say that large $r'$ generally means large c.

2. The difference between the one-step prediction and the interpolation method lies in the filter gain normalization factor $1/\alpha_{m_0}$. In the one-step prediction method, $\alpha_{m_1}$, thus, the possibility of larger-than-one filter coefficients $\alpha_m$ exists. Such filter coefficients would of course amplify clutter and noise effects. In the interpolation method, $\alpha_{m_0}$ is the difference equation coefficient of maximum magnitude. Thus, no filter coefficient can have value larger than one.

3. For the desired target, $R_W(t)$ is given by the Z transform of Equation (4) and thus Equation (30) can be written as

$$E(Z) = \frac{1}{z^{N+m_0}} \sum_{k=0}^{N-1} \sum_{i=m_0} a_{m_i} \frac{1}{(1-z^{-1}z_{m_i})} \bigg[ \sum_{j=1}^{N} \frac{Q(z)}{(1-z^{-1}z_j)} \bigg]$$

$$= \frac{1}{z^{N+m_0}} \sum_{k=0}^{N-1} \sum_{i=m_0} a_{m_i} \frac{1}{(1-z^{-1}z_{m_i})} \bigg[ \sum_{j=1}^{N} \frac{Q(z)}{(1-z^{-1}z_j)} \bigg]$$

* $e^{t_e-N+T+m_0T}$

$$e^2(t)(((t_e-t_s)/T_B)}$$

$$t=t_s+m_0T$$
where \( N_1 \) is the number of complex resonances present in the waveform and \( N \) is the number of all possible complex resonances of the desired target present within the radar bandwidth and used for target identification purposes. Since certain target resonances may not be excited for some radar locations and orientations, \( N_1 \) and \( N \) are not necessarily equal. \( Q(Z) \) is a polynomial of order \( N_1 \) in \( Z^{-1} \).

From Equation (33), we see that the predictor-correlator identification process is basically a pole-removal process. Furthermore, the process of pole removal is performed by putting zero's at the locations of the poles.

In the case of \( N_1 = N \),

\[
E(Z) = \frac{1}{a_m} \sum_{k=0}^{N+m_0} \left[ \frac{1}{k} Z^{-k} Q(Z) \right].
\]

Thus

\[
e(nT_B) = \frac{1}{a_m} q(nT_B) = 0 \text{ for } nT_B \geq m_0 T
\]

where

\[
q(nT_B) = r^{-1} \left[ \sum_{k=0}^{N+m_0} \left( \frac{1}{k} Z^{-k} Q(Z) \right) \right]
\]

where \( r^{-1} \) is the inverse \( Z \) transform operation. Since \( Q(Z) \) is a polynomial of order \( N \) in \( Z^{-1} \), \( q(nT_B) \) is zero for \( nT_B \geq m_0 T \) \([54-56]\). Thus, the instantaneous error \( e(nT_B) \) is zero for \( nT_B \geq m_0 T \) and the mean-square error would also be zero in this time region. The above derivation is based on the assumption that the resonance time region of the waveform starts at \( t=0 \). Since the resonance region of the waveforms considered in this study is assumed to start at \( t=t_0 \), the mean-square error would be zero for \( t \geq t_0 + n T \). This is the lower limit of the error-calculation interval as defined in Equations (21) and (24).

In the case of \( N_1 < N \),

\[
E(Z) = \frac{1}{a_m} \sum_{k=0}^{N+m_0} \left[ \frac{1}{k} Z^{-k} Q(Z) \right]^{N-N_1} (1-Z^{-1}Z_j)
\]
Thus
\[ e(nT_B) = q'(nT_B) \]  \hspace{1cm} (39)

where
\[ q'(nT_B) = c^{-1} \left[ \sum_{k=0}^{N+\mu_0} \frac{1}{D} \frac{Q(Z)}{1 - Z^{-1} Z_j} \right] \]  \hspace{1cm} (40)

Since \( Q(Z) \) is of degree \( N_1 \) in \( Z^{-1} \), thus \( q'(nT_B) \) is again zero for \( nT_B \neq m_0 T \). Thus putting the number of all possible extracted resonances of the desired target in the identifier assures a zero error and thus a unity correlation coefficient for the desired target waveforms from all radar locations and orientations. If not all possible extracted resonances are used for target identification, the possibility of \( N_1 > N \) exists and in this case,
\[ E(Z) = \frac{1}{\sigma_m^2} \left[ \sum_{k=0}^{N+\mu_0} \frac{1}{D} \frac{Q(Z)}{1 - Z^{-1} Z_j} \right] \]  \hspace{1cm} (41)

The instantaneous error has poles in its \( Z \) transform, causing it to be a waveform of infinite duration [54-56]. Thus, a large mean-square error could occur for a desired-target waveform, possibly causing the correlation coefficient to be much less than one.

4. For an undesired target, the instantaneous error depends on the processed waveform \( r_M(t) \) as well as the locations of the zero's in the identifier. Small error could result only in the cases where the undesired-target waveform is closely characterized by a set of complex resonances which are approximately equal to the desired-target resonances (i.e., the zeros in the identifier). In the one-pole case where,
\[ R_M(Z) = \frac{1}{1 - Z^{-1} Z_1} \]

\[ C(Z) = (1 - Z^{-1} Z_2) \]  \hspace{1cm} (42)

where \( R_M(Z) \), the \( Z \) transform of the measured waveform is assumed to have only one pole at \( Z_1 \) with residue 1. \( C(Z) \), the identification filter is assumed to consist of a zero at \( Z_2 \). The error can be expressed as
Thus, 

$$E(Z) = \sum_{i=0}^{N+m_0} Z^{-i} \frac{1}{1-Z^{-1}Z_2}$$

(43)

Thus,

$$\epsilon' = \left( \frac{|Z_1-Z_2|}{\alpha_{m_0}} \right)^2 \int \frac{r_2(t)}{((t_s-t_0)/T_0)}$$

(44)

where $|\cdot|$ denotes complex magnitude. Hence the total squared error is directly proportional to the magnitude square of the difference between the locations of the pole and the zero.

In a two-pole case where

$$R_M(Z) = \frac{1}{1-Z^{-1}Z_1} + \frac{1}{1-Z^{-1}Z_2^*}$$

(45)

$$C(Z) = (1-Z^{-1}Z_2)(1-Z^{-1}Z_2^*)$$

where $[\cdot]^*$ denotes complex conjugation. The error can be expressed as

$$E(Z) = \sum_{i=0}^{N+m_0} Z^{-i} \frac{1}{1-Z^{-1}Z_1} \frac{1}{1-Z^{-1}Z_2^*}$$

(46)
or

\[ E(Z) = \frac{1}{\alpha_{m_0}} Z^{-N+m_0} \sum_{k=0}^{\infty} z^k \left\{ (1-Z^{-1}Z_2^*) + (1-Z^{-1}Z_2) + \left[ \frac{(Z_1-Z_2) + (Z_1^*-Z_2^*)}{1-Z^{-1}Z_1 + 1-Z^{-1}Z_1^*} \right] + \left[ \frac{(Z_1-Z_2)Z_2 + (Z_1^*-Z_2^*)Z_2^*}{1-Z^{-1}Z_1 + 1-Z^{-1}Z_1^*} \right] \right\}. \] (47)

The total square error \( \epsilon' \) is independent of the first two terms on the right hand side of Equation (47). Furthermore, the inverse Z transform of the last two terms are given by [54]

\[ \zeta^{-1} \left[ Z^{-1} \left( \frac{Z_1-Z_2}{1-Z^{-1}Z_1} + \frac{Z_1^*Z_2^*}{1-Z^{-1}Z_1^*} \right) \right] = ||Z_1-Z_2|| e^{\alpha_1(t-T)} \]

\[ \times \cos[\omega_1(t-T) + \theta_1] \] (48)

and

\[ \zeta^{-1} \left[ Z^{-2} \left( \frac{(Z_1-Z_2)Z_2}{1-Z^{-1}Z_1} + \frac{(Z_1^*-Z_2^*)Z_2^*}{1-Z^{-1}Z_1^*} \right) \right] \]

\[ = ||Z_1-Z_2|| \left| \frac{Z_2}{1-Z^{-1}Z_1^*} \right| e^{\alpha_1(t-2T)} \]

\[ \times \cos[\omega_1(t-2T) + \theta_1 + \theta_2] \] (49)

where \( \omega_1 \) and \( \omega_2 \) are the arguments of the complex numbers \((Z_1-Z_2)\) and \(Z_2\), respectively.

From Equations (47) and (48), we see that

\[ \omega(t) = \frac{1}{\alpha_{m_0}} ||Z_1-Z_2|| e^{\alpha_1(t-T)} \left\{ \cos[\omega_1(t-T)+\theta_1] + \frac{1}{||Z_2||} e^{\frac{-\alpha_1 T}{2}} \cos[(\omega_1(t-T)+\theta_1) + (\omega_1 T + \theta_2)] \right\}. \] (50)
Thus, the instantaneous error depends on the following three items:

a. The amplitude factor \( ||Z_1-Z_2||^2 = e^{2\alpha_1 T} + e^{2\alpha_2 T} - 2e^{\text{im}(\omega_1+\omega_2)T} \cos(\omega_1-\omega_2)T \), where \( s = \omega_1 + j\omega_2 \) is the location of the zero of the filter in the \( s \) plane.

b. The factor \( 2e^{\alpha_1 T} ||Z_2|| = 2e^{\alpha_1 T} \).

c. The phase term \( \omega_1 T + \omega_2 T \).

All of the above three items are dependent on the sampling interval \( T \). Thus, in designing the identification radar, the value(s) of \( T \) should be chosen to maximize \( \epsilon' \) by considering its dependence on the above three items. In maximizing \( \epsilon' \), we note the following guidelines:

a. Small values* of \( T \) result in \( ||Z_1-Z_2|| \) approaching zero. This causes \( \epsilon' \) to approach zero. Thus, small \( T \) values offer no identification capability.

b. Large values** of \( T \) also result in \( ||Z_1-Z_2|| \) approaching zero. Thus, large \( T \) values offer no identification capability.

c. Intermediate value of \( T \) should be chosen to satisfy the following conditions as closely as possible:

i. \( e^{2\alpha_1 T}, e^{2\alpha_2 T}, e^{(\omega_1+\omega_2)T} \) approach 1,

ii. \( (\omega_1-\omega_2)T \) approaches 0,

iii. \( (\omega_1+\omega_2)T \) approaches 2\( \pi \),

iv. To prevent severe aliasing effects, we require that \( mT \) is such that \( mT \) and \( \omega_1 T \) approach 0.

---

* Small \( T \) in this case means that the quantities \( (\omega_1-\omega_2)T \) approach 0 and the quantities \( e^{\alpha_1 T}, e^{\alpha_2 T}, e^{(\omega_1+\omega_2)T} \) approach 1.

** Large \( T \) in this case means that the quantities \( e^{\alpha_1 T}, e^{\alpha_2 T}, e^{(\omega_1+\omega_2)T} \) approach 0.
Conditions I. and II. maximize the amplitude factor \[|Z_1-Z_2|\]. Conditions I. and III. make sure that the second term in Equation (50) is maximized and has the same sign as the first term. Conditions II. and III. require that 
\[2\pi \omega_2 T = \pi.\] Condition I. requires that \(T\) be as small as possible. These, together with condition IV indicate that a reasonable compromise is to choose \(T\) such that \(\omega_2 T = \pi\).

Although the above analysis is based on a two-pole system, for systems of more than two poles, the above results are expected to be reasonably valid when \(\omega_1\) is taken to be the imaginary part of the dominant pole of the measured waveform to be identified and \(\omega_2\) is taken to be the imaginary part of the zero of the identification filter which is closest to the dominant pole. In practical target identification situations, the waveforms from the desired as well as the undesired targets almost always contain more than two poles (see Chapter III). Furthermore, the dominance of the resonances of the undesired target is generally unknown. Thus, for better identification performance, it is advisable to base the identification decision-making process on more than one value of \(T\). Based on the analysis in this section, the smallest "effective" value of \(T\) is in the neighborhood of \(T_N\) where

\[T_N = \frac{\omega_m}{2\pi f_M} = \frac{1}{2\pi f_M},\] (51)

and \(\omega_m = 2\pi f_M\) is the maximum imaginary part of the desired-target resonances. In applying the criterion given by Equation (51) to choose the values of \(T\) for target identification, the word neighborhood should be emphasized and taken to mean that, although the single value of \(T\) for optimum target-separation performance cannot be found without the complete knowledge of the undesired-target waveform, the value \(T = T_N\) should give reasonable, if not the optimum performance. Furthermore, for target identification based on more than one value of \(T\), the region of \(T\) values chosen should contain \(T_N\).

The analysis presented in this section are generally supported by the identification results obtained in this study. Identification results are shown in Section F of this chapter. 

* It is assumed that \(\omega_2 > \omega_1\). Note that the design of the low-pass filter in the preprocessor of the identification radar assures that frequencies higher than \(\omega_2\) will be highly attenuated. Thus, \(\omega_2 > \omega_1\) is a valid assumption.
1. The Identification Algorithm

In this study, a "single-look" identification algorithm was used. An identification decision was made for every measured backscattered waveform. The identification algorithm was one of threshold identification based on the values of \( r(T) \) evaluated at different values of \( T \), and the average value of \( r(T) \) denoted by \( \langle r(T) \rangle \). Thus, the decision algorithm was

\[
\begin{align*}
\text{"Desired Target" when} & \quad r(T_{0i}) < r_{THi} \quad \text{for } i=1 \text{ and } 2 \ldots \text{ and } I \\
\text{and } r(T_0) \cdot \frac{1}{I} \geq r_{THA} & \\
\text{"Undesired Target" when} & \quad r(T_{0i}) < r_{THi} \quad \text{for } i=1 \text{ or } 2 \ldots \text{ or } I \\
or & \quad r(T_0) < r_{THA}
\end{align*}
\]

\( r_{THi} \) is the identification threshold for \( r(T) \) at the \( T \) value of \( T_{0i} \). \( T_{0i} \)'s are the values of \( T \) chosen for optimum identification performance. \( r_{THA} \) is the identification threshold for the average of \( r(T) \) taken over all the values of \( T_{0i} \). Thus, for a single measured waveform, we evaluate its correlation function \( r(T) \) at all chosen values of \( T_{0i} \) and compare the values \( r(T_{0i}) \) and \( \langle r(T_0) \rangle \) to \( r_{THi} \) and \( r_{THA} \), respectively for an identification decision. Figure 20 illustrates the decision-making process. In Figure 20, the value of the \( r(T) \) curve represented by "dots" at \( T_{01}, T_{02} \ldots T_{05} \) as well as \( \langle r(T_0) \rangle \) are greater than their corresponding thresholds hence, the targets it represents is by decision a "desired" target. The \( r(T) \) curve represented by "boxes" has at least one of the values \( r(T_{0i}) \) or \( \langle r(T_0) \rangle \) below its corresponding threshold, thus, the target it represents is by decision an "undesired" target.

\( T_{0i} \)'s are the value of \( T \) chosen for optimum identification performance. The values of \( T_{0i} \) are closely related to the value of the resonances of the desired target and Equation (51). Details concerning the values of \( T_{0i} \)'s will be further discussed in the next section. In Equation (52), quotation marks are used to signify a decision, i.e., "Desired Target" is by decision a desired target while in reality it could be an undesired target (in case of false alarm).

The identification algorithm given in Equation (52) reduces to its simplest form when only one value of \( T_{0i} \) is considered. In this case, the identification algorithm is
Figure 20. The decision-making process for the multiple-threshold identification algorithm.
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"Desired target" when \( r(i_0) < TH \)

"Undesired target" when \( r(i_0) > TH \)

(53)

In the following section, the predictor-correlator identification method is applied to the processed waveforms. Identification performance will be presented and discussed.

F. Performance of the Predictor-Correlator Identifier

In order to demonstrate the effectiveness of the predictor-correlator, a set of identification performance based on a single value of \( r(T) \) were obtained by applying the predictor-correlator alone (i.e., without the filter and the detector) to the difference waveforms. Identification results based on multiple values of \( r(T) \) and with the filter and detector operations inserted will be presented later in this section. Identification performance was characterized by a \( r(T) \) curve. Typical \( r(T) \) curves are shown in Figure 21. In this case, the identifier was set to identify the mine-like target in a wet ground condition.

From Figure 21, we find that typical \( r(T) \) curves have the following features:

1. The value of \( r(T) \) is approximately 1 for small values of \( T \). This is true for \( r(T) \) of both the desired and undesired targets. This region of \( T \) has no identification capability.

2. The region of \( T_0 \) where "optimal" identification performance occurs is in the immediate neighborhood of \( T_N \) where \( T_M \) is given by Equation (51). In this case for identification of the mine-like target in a wet ground condition. The resonances of the mine-like target as given in Table 1c was used. Thus, \( f_M = 420 \text{ MHz} \), corresponding to the rounded \( T_N \) value of \( 6 \text{ T}_B \) (or 1.2 ns). For the \( r(T) \) curves given in Figure 21, the region of \( T_0 \) is from \( 6 \text{ T}_B \) to \( 11 \text{ T}_B \). This result supported the observations made in Section D of this chapter. The fact that the region of effective values of \( T \) contained values larger than \( T_N \) indicated that the dominant pole(s) in the copper sheet waveform had imaginary parts lower than 420 MHz.

3. The value of \( r(T) \) fluctuates when \( T \) is much larger than \( T_N (T > 2T_N) \). This region of \( T \) has no identification capability. Besides the reason given in Section D of this chapter, this can also be attributed to the following.
Figure 21. Typical \( \rho(T) \) curves for the identification of the mine-like target in wet ground.
First, aliasing of the high frequency zeros in the identifier makes these zeros ineffective. Second, the size of the error interval of the error \( \hat{y} \) decreases as \( T \) increases, for the number of instantaneous error samples used in the calculation of \( \hat{y} \) decreases. Third, because of the large value of \( T \), only the tail end of the measured waveform is used in the calculation of \( \hat{y} \). This region of the measured waveform has low signal level.

The above features of the \( \nu(T) \) curves were generally observed in almost all cases considered. The significance of these features is that optimal identification performance occurs in a confined range of \( T \) values in the immediate neighborhood of \( T_N \). Hence one knows a priori the value or range of values of \( T \) on which to base the implementation of the radar system. These features are again demonstrated in the \( \nu(T) \) curves given in Figures 22 and 23 for the identification of the mine-like target and the brass cylinder in dry ground, respectively.

In this study, the criterion for optimum identification performance was to require perfect identification of desired-target returns, and thus optimal performance was the one with the lowest false alarm probability obtained by varying \( T \). Single-looking identification and false alarm probabilities are estimated in a frequency of occurrence sense. Thus,

\[
P_1 = \frac{N_2}{N_1}, \quad (54)
\]

\[
P_{FA} = \frac{N_4}{N_3}, \quad (55)
\]

where

\( P_1 \) - Probability of identification

\( P_{FA} \) = Probability of false alarm

\( N_1 \) = Total number of desired-target waveforms within the identification range.

\( N_2 \) = Number of desired-target signals which are correctly identified within the identification range.

\( N_3 \) = Total number of other-target waveforms.
Figure 22. Typical $\rho(t)$ curves for the identification of the mine-like target in dry ground.
Figure 23. Typical \( p(T) \) curves for the identification of the brass cylinder in dry ground.
The number of other-target waveforms which are mistaken to be desired-target waveforms.

Note that $N_3$, $N_4$ basically determine the accuracy or "confidence interval" [65] of the above estimates of the identification statistics.

To see the degree of separation between the mine-like target and other subsurface targets, consider the distribution of correlation coefficients shown in Figure 24. In this case, the system is set to identify the mine-like target in wet ground. From Figure 24, we see that, for $P_1 = 100\%$, and $T_0 = 9T_B$, the minimum separation margin between the mine-like target and other targets is 0.93 in the value of $\mu(T_0)$. In this case, for an identification performance estimate of $P_1 = 100\%$, $P_{FA} = 0\%$ one can set the identification threshold $\mu_{TH}$ at a value ranging from -0.26 to 0.167. The maximum value of $\mu_{TH}$ is 0.167. The correlation coefficients for the mine-like target shown in Figure 24 include only cases measured within the identification range $R_{ID}$. In this study, identification range is the radar range measured from the center of the target. Correlation coefficients for the other targets include all cases measured.

A summary of optimal single-look identification performance is given in Table 4 (for details, see Appendix E). Estimates of $P_1 = 100\%$, $P_{FA} = 0\%$ identification performance were obtained for the identification range of 30 cm measured from the center of the mine-like target and the brass cylinder.

This set of identification performance basically established the fact that the predictor-correlator identification method worked in its simplest form and with a minimum amount of preprocessing. However, in a practical system, one would prefer to have the filter and detector inserted for better performance in more severe clutter/noise environment provided that the amount of time taken to perform these operations are not too large to make them non-cost-effective. Furthermore, the multiple-threshold algorithm would also provide better performance.

In target identification with detection and multiple-threshold operations, the ranges of the detection parameters, i.e., waveform energy, peak timing and peak magnitude must be chosen. Furthermore, the values of $T_0$ as well as the identification thresholds $\mu_{TH1}$ and $\mu_{TH2}$ must be determined. In this study, these parameters were experimentally determined via the following procedure:

1. The ranges of the detection parameters were chosen to be the ranges of these parameters of the waveforms measured from the desired target within the identification range.

2. Choose the range of $T_0$ values based on the conditions given in Section D of this chapter.
Figure 24. Distribution of correlation coefficients for the identification of the mine-like target in wet ground. \( R_{ID}=30 \text{ cm} \).
TABLE 4
SUMMARY OF SINGLE-LOOK IDENTIFICATION PERFORMANCE
OF THE SHORT-CABLE SYSTEM
P1=100% For All Cases

<table>
<thead>
<tr>
<th>DESIRED TARGET</th>
<th>GROUND CONDITION</th>
<th>T0</th>
<th>TH</th>
<th>R1D  (cm)</th>
<th>PFA</th>
<th>NUMBER OF WAVEFORMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET</td>
<td>WET</td>
<td>7TB-9TB</td>
<td>0.183</td>
<td>30</td>
<td>0%</td>
<td>12 12</td>
</tr>
<tr>
<td>MINE-LIKE TARGET</td>
<td>DRY</td>
<td>7TB-9TB</td>
<td>0.483</td>
<td>15</td>
<td>0%</td>
<td>5  3</td>
</tr>
<tr>
<td>MINE-LIKE TARGET</td>
<td>Icy</td>
<td>7TB-9TB</td>
<td>0.423</td>
<td>30</td>
<td>0%</td>
<td>9  9</td>
</tr>
<tr>
<td>BRASS CYLINDER</td>
<td>Icy</td>
<td>5TB-7TB</td>
<td>0.675</td>
<td>30</td>
<td>0%</td>
<td>9  9</td>
</tr>
</tbody>
</table>

*PERFORMANCE FOR R1D=30 cm WAS NOT OBTAINED IN THIS CASE.
R1D = IDENTIFICATION RANGE, MEASURED FROM CENTER OF TARGET

3. Choose the identification thresholds to be the minimum values of T0I and T0 of the desired-target waveforms measured within the identification range.

An example is given below to clarify the above procedure. From the waveforms measured from a mine-like target in a wet ground condition, we evaluated their detection parameters (as tabulated in Table 5) and determined the minimum and maximum of these parameters. The ranges of these parameters were used as the desired ranges of the detection parameters in the detector. With the extracted resonances from the measured waveforms (as given in Table 6), and the conditions given in Section D of this chapter, we chose the range of T0I values to be from (T0-2TB) to 2TN. In this case T0=428 MHz, thus

\[ T_N = \left[ \frac{1}{2 \times 428 \times 10^6} \right]^* = 5TB \]

* [ ] denotes greatest integer.
TABLE 5
DETERMINING THE DETECTION PARAMETERS FOR IDENTIFICATION OF THE MINE-LIKE TARGET IN A WET GROUND CONDITION.
\( R_{ID} = 30 \) cm

<table>
<thead>
<tr>
<th>ANTEA LOCATION</th>
<th>C</th>
<th>15 cm S</th>
<th>15 cm W</th>
<th>30 cm S</th>
<th>30 cm W</th>
<th>15 cm E</th>
<th>15 cm W</th>
<th>20 cm S</th>
<th>20 cm W</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{max} ) *</td>
<td>17</td>
<td>27</td>
<td>29</td>
<td>3d</td>
<td>69</td>
<td>46</td>
<td>71</td>
<td>60</td>
<td>67</td>
<td>27</td>
<td>69</td>
</tr>
<tr>
<td>( m ) **</td>
<td>3.99696</td>
<td>2.65840</td>
<td>2.65925</td>
<td>1.78342</td>
<td>1.70674</td>
<td>1.18873</td>
<td>2.74239</td>
<td>1.88786</td>
<td>1.18873</td>
<td>2.99696</td>
<td></td>
</tr>
<tr>
<td>( E_M ) ***</td>
<td>0.12784</td>
<td>0.57511</td>
<td>0.68460</td>
<td>0.33775</td>
<td>0.25890</td>
<td>0.22767</td>
<td>0.16916</td>
<td>0.20656</td>
<td>0.20823</td>
<td>0.12784</td>
<td>0.68460</td>
</tr>
</tbody>
</table>

* \( t_{max} \) = peak timing, in units of \( T_B \)

** \( m \) = peak magnitude, in units of 200 mV

*** \( E_M \) = waveform energy, in units of (200 mV)².
Definition of \( E_M \) is given in Chapter II.
TABLE 6
AVERAGE EXTRACTED RESONANCES OF THE MINE-LIKE TARGET IN A WET GROUND CONDITION

<table>
<thead>
<tr>
<th>POLE (REAL)*</th>
<th>POLE (IMAG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.71536397E8</td>
<td>6.1601933 E7</td>
</tr>
<tr>
<td>-5.73125538E7</td>
<td>1.32122486E8</td>
</tr>
<tr>
<td>-2.87494683E8</td>
<td>2.27030133E8</td>
</tr>
<tr>
<td>-1.82905090E8</td>
<td>3.07411043E8</td>
</tr>
<tr>
<td>-9.76454733E7</td>
<td>4.28447900E8</td>
</tr>
</tbody>
</table>

*Real and imaginary parts of the extracted poles are in nepers/s and Hz, respectively.

With the values of $T_{ni}$, we evaluate the values of $\mu(T_{ni})$ and $\langle \rho(T_n) \rangle$ for the all measured desired-target waveforms. The minimum of these values are chosen to be the identification thresholds. This is illustrated in Table 7.

Table 8 summarizes a set of single-look identification performance based on the additional preprocessing and the multiple-threshold algorithm. Note that the size of the ensembles of waveforms considered indicates a better estimate of the identification statistics. In obtaining this set of identification performance, the region of $T_0$ values was chosen to be from $(T_N-T_B)$ to $2T_N$. Details concerning the identification results are given in Appendix E.

The identification statistics discussed so far were obtained with the identifier "tuned" to the right ground condition, e.g., the wet-ground resonances of the mine-like target were used to identify the mine-like target in that wet ground condition. If the identifier is not tuned, identification performance will degrade, e.g., for the waveforms considered in Table 4, when the dry-ground resonances were used to identify the mine-like target in wet ground, performance degraded to $P_f=90\%$, $P_{fa}=16.6\%$. Methods for on-location calibration of the ground condition and automatic tuning of the identification radar to ground condition is currently being pursued. One method is based on the backscattered waveforms from thin wires measured using the same pulse radar system. On-location calibration of the ground condition and automatic tuning of the identifier to the ground condition are discussed in Chapter IX.
**TABLE 7**

DETERMINING THE IDENTIFICATION THRESHOLDS FOR THE
MINE-LIKE TARGET IN A WET GROUND CONDITION.
*R_{10}=30 cm*

<table>
<thead>
<tr>
<th>ANTEENA LOCATION</th>
<th>0°</th>
<th>15 cm, S</th>
<th>30 cm, N</th>
<th>30 cm, W</th>
<th>15 cm, E</th>
<th>30 cm, F</th>
<th>30 cm, W</th>
<th>MINIMUM</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>(T_{0})</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>(4^{T}_{B})</em></td>
<td>.984</td>
<td>.948</td>
<td>.975</td>
<td>.996</td>
<td>.996</td>
<td>.971</td>
<td>.998</td>
<td>.934</td>
</tr>
<tr>
<td><em>(5^{T}_{B})</em></td>
<td>.920</td>
<td>.667</td>
<td>.739</td>
<td>.927</td>
<td>.905</td>
<td>.943</td>
<td>.808</td>
<td>.635</td>
</tr>
<tr>
<td><em>(6^{T}_{B})</em></td>
<td>.128</td>
<td>.0871</td>
<td>.209</td>
<td>.0331</td>
<td>.642</td>
<td>.530</td>
<td>.240</td>
<td>.354</td>
</tr>
<tr>
<td><em>(7^{T}_{B})</em></td>
<td>.499</td>
<td>.243</td>
<td>.377</td>
<td>.568</td>
<td>.573</td>
<td>.453</td>
<td>.390</td>
<td>.258</td>
</tr>
<tr>
<td><em>(8^{T}_{B})</em></td>
<td>.606</td>
<td>.0615</td>
<td>.099</td>
<td>.0860</td>
<td>.589</td>
<td>.522</td>
<td>.351</td>
<td>.150</td>
</tr>
<tr>
<td><em>(9^{T}_{B})</em></td>
<td>.924</td>
<td>.118</td>
<td>.200</td>
<td>.227</td>
<td>.716</td>
<td>.639</td>
<td>.402</td>
<td>.820</td>
</tr>
<tr>
<td><em>(10^{T}_{B})</em></td>
<td>.878</td>
<td>.224</td>
<td>.0566</td>
<td>.291</td>
<td>.177</td>
<td>.413</td>
<td>.669</td>
<td>.547</td>
</tr>
<tr>
<td><em>(T_{0})</em></td>
<td>.70442</td>
<td>.25937</td>
<td>.31965</td>
<td>.41568</td>
<td>.65683</td>
<td>.63864</td>
<td>.54245</td>
<td>.52819</td>
</tr>
</tbody>
</table>
Identification is degraded when the radar frequencies do not properly span the target resonances. This is demonstrated in Chapter V.

**TABLE 8**

**SUMMARY OF SINGLE-LOOK IDENTIFICATION PERFORMANCE OF THE SHORT-CABLE SYSTEM BASED ON ADDITIONAL PREPROCESSING AND MULTIPLE-THRESHOLD ALGORITHM**

$P_I=100\%$ For All Cases

<table>
<thead>
<tr>
<th>Desired Target</th>
<th>Ground Condition</th>
<th>$T_{oi}$</th>
<th>$\rho_{TH1}$</th>
<th>$\rho_{THA}$</th>
<th>RID (cm)</th>
<th>$P_{FA}$</th>
<th>Number of Waveforms</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET</td>
<td>WET, 1</td>
<td>5TB</td>
<td>0.946</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6TB</td>
<td>0.667</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7TB</td>
<td>-0.209</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8TB</td>
<td>0.243</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9TB</td>
<td>-0.0615</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10TB</td>
<td>-0.118</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11TB</td>
<td>0.224</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MINE-LIKE TARGET</td>
<td>WET, 2</td>
<td>5TB</td>
<td>0.445</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6TB</td>
<td>-0.488</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7TB</td>
<td>0.127</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8TB</td>
<td>0.243</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9TB</td>
<td>0.289</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10TB</td>
<td>0.221</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11TB</td>
<td>0.436</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12TB</td>
<td>-0.259</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 8 (Cont.)

<table>
<thead>
<tr>
<th>BRASS CYLINDER</th>
<th>WET</th>
<th>5TB</th>
<th>6TB</th>
<th>7TB</th>
<th>8TB</th>
<th>9TB</th>
<th>10TB</th>
<th>11TB</th>
<th>12TB</th>
<th>34073</th>
<th>30</th>
<th>.97%</th>
<th>9</th>
<th>103</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUMINUM SPHERE</td>
<td>WET</td>
<td>5TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>197</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.481</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.600</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-.106</td>
<td>37</td>
<td></td>
<td>6.12%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.218</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.189</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>11TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.103</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>.341</td>
<td></td>
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</tbody>
</table>
CHAPTER V
EFFECTS OF RADAR BANDWIDTH ON THE CHARACTERIZATION
AND IDENTIFICATION OF SUBSURFACE TARGETS

A. Introduction

The target resonances present in the backscattered waveforms depend on the bandwidth of the radar system. Target resonances residing near the band edge(s) or outside the bandwidth of the radar system are either weakly excited or not excited at all. Thus, when the radar bandwidth is reduced, the number of target resonances present in the backscattered waveforms will decrease accordingly. In this study, a set of data was obtained with an additional 200 m of connecting cables (RG-8) inserted in the system to keep the equipment indoors during inclement weather. These cables acted as a low-pass filter with attenuation of 30 dB at 400 MHz and thus reduced the radar bandwidth. Such bandwidth reduction was found to degrade identification performance for certain subsurface targets under consideration.

B. Processed Waveforms Obtained With
the Long-Cable System

Typical processed waveforms obtained with the long-cable system are shown in Figure 25. A quick comparison between the waveforms in Figures 7, 9, and 25 indicates the severe loss of high frequency in the waveforms of the mine-like target and wood board. Furthermore, there was a significant loss of signal amplitude for all waveforms.

C. Extracted Resonances

The average extracted resonances of the long-cable waveforms from the subsurface targets are given in Tables 9 and 10. A comparison between the extracted resonances in Tables 3 and 9, 10 indicates a general loss of high-frequency resonances in the long-cable waveforms. The loss of high-frequency content causes the high frequency resonances to be either weakly excited or not excited at all. A comparison between the resonances extracted from the two sets of mine-like target waveforms (as plotted in Figure 26) shows that, in the long-cable system, the resonance of the mine-like target at 300 MHz was not excited, while the resonance at 400 MHz was only weakly excited.
Figure 25. Typical long-cable processed waveforms from the mine-like target and the wood board.
Figure 26. Average extracted resonances from the long and short-cable mine-like target waveforms.
### TABLE 9
AVERAGE EXTRACTED RESONANCES OF THE MINE-LIKE TARGET AND THE BRASS CYLINDER IN THE LONG-CABLE SYSTEM

<table>
<thead>
<tr>
<th></th>
<th>MINE-LIKE TARGET</th>
<th></th>
<th>BRASS CYLINDER</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY GROUND</td>
<td></td>
<td>DRY GROUND</td>
<td></td>
</tr>
<tr>
<td>POLE</td>
<td>REAL PART (NEPERS/s)</td>
<td>POLE</td>
<td>REAL PART (NEPERS/s)</td>
<td>POLE</td>
</tr>
<tr>
<td></td>
<td>-.2212043E9</td>
<td>=.6866711E8</td>
<td>-.2769107E9</td>
<td>=.0000000</td>
</tr>
<tr>
<td></td>
<td>-.1330764E9</td>
<td>=.1213923E9</td>
<td>-.1904636E9</td>
<td>=.7836537E8</td>
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<tr>
<td></td>
<td>-.2593455E9</td>
<td>=.2503563E9</td>
<td>-.2233100E9</td>
<td>=.9971379E8</td>
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<tr>
<td></td>
<td>-.2429505E9</td>
<td>=.4063677E9</td>
<td>-.0430810E9</td>
<td>=.1681942E9</td>
</tr>
<tr>
<td></td>
<td>0701791E9</td>
<td>=.2964066E9</td>
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<td></td>
</tr>
</tbody>
</table>

### TABLE 10
AVERAGE EXTRACTED RESONANCES OF THE ALUMINUM SPHERE, COPPER SHEET AND THE WOOD BOARD IN THE LONG-CABLE SYSTEM

<table>
<thead>
<tr>
<th></th>
<th>ALUMINUM SPHERE</th>
<th></th>
<th>COPPER SHEET</th>
<th></th>
<th>WOOD BOARD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY GROUND</td>
<td></td>
<td>DRY GROUND</td>
<td></td>
<td>WET GROUND</td>
<td></td>
</tr>
<tr>
<td>POLE</td>
<td>REAL PART (NEPERS/s)</td>
<td>POLE</td>
<td>REAL PART (NEPERS/s)</td>
<td>POLE</td>
<td>REAL PART (NEPERS/s)</td>
<td>IMAG PART (Hz)</td>
</tr>
<tr>
<td></td>
<td>-.1393208E9</td>
<td>=.6465970E8</td>
<td>-.1850247E9</td>
<td>=.6443022E8</td>
<td>-.1267105E9</td>
<td>=.5738908E8</td>
</tr>
<tr>
<td></td>
<td>-.1709903E9</td>
<td>=.1576600E9</td>
<td>-.2442978E9</td>
<td>=.8136559E8</td>
<td>-.1282961E9</td>
<td>=.8721573E8</td>
</tr>
<tr>
<td></td>
<td>-.46776075E9</td>
<td>=.2148951E9</td>
<td>-.3748783E9</td>
<td>=.1701710E9</td>
<td>-.1931582E9</td>
<td>=.1958087E9</td>
</tr>
<tr>
<td></td>
<td>-.2503479E9</td>
<td>=.3415180E9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

80
D. Target Identification Performance

Single-look identification performance is summarized in Table 11.* As expected, identification performance degraded. The drastic degradation in the performance for the identification of the mine-like target and the wood board clearly demonstrated the importance of high frequencies for the identification of these two targets.

<table>
<thead>
<tr>
<th>DESIRED TARGET</th>
<th>GROUND CONDITION</th>
<th>T0</th>
<th>PTH</th>
<th>RID  (cm)</th>
<th>PFA</th>
<th>NUMBER OF WAVEFORMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET</td>
<td>DRY</td>
<td>7T_B</td>
<td>.675</td>
<td>30</td>
<td>33.55%</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>152</td>
</tr>
<tr>
<td>BRASS CYLINDER</td>
<td>DRY</td>
<td>10T_B</td>
<td>.600</td>
<td>30</td>
<td>4.49%</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>156</td>
</tr>
<tr>
<td>ALUMINUM SPHERE</td>
<td>DRY</td>
<td>10T_B</td>
<td>.867</td>
<td>52</td>
<td>9.29%</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>140</td>
</tr>
<tr>
<td>COPPER SHEET</td>
<td>DRY</td>
<td>9T_B</td>
<td>.964</td>
<td>40</td>
<td>4.35%</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>138</td>
</tr>
<tr>
<td>WOOD BOARD</td>
<td>WET</td>
<td>7T_B</td>
<td>.823</td>
<td>45</td>
<td>23.98%</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>138</td>
</tr>
</tbody>
</table>

The importance of the high-frequency resonances of the mine-like target stems from the fact that its high-frequency resonances are dominant (see residues of target resonances in Appendix C). An attempt to identify this target without strongly exciting its dominant resonances results in the poorer identification performance. To improve target identification performance, the radar must be able to transmit and receive more high-frequency energy in the vicinity of these high-order resonances. The short-cable system discussed previously represented an improvement over the long-cable system. However, much more

*This set of identification results was obtained based on threshold identification with one value of T0 and without detection and filtering.
improvement can be made in the various components of the pulse radar system to provide a better "match" between the system bandwidth and the bandwidth in which the dominant target resonances reside. One of these components is the antenna system.

For the identification of the plastic mine-like target, the crossed-dipole antenna with arm length of 0.6 m (2 feet) did not provide a "good" match between the radar system bandwidth and the bandwidth of the target resonances. The extracted resonances shown in Figure 14 indicated that the antenna resonance was not even near the high-order resonances of the mine-like target. Such mismatch of bandwidths results in the low level of correlation coefficients as tabulated in Table 8. For better characterization and identification of the mine-like target, the frequency of the antenna resonance needs to be increased. One easy way to accomplish such increase is to reduce the size of the antenna. In this study, a smaller crossed-dipole antenna with arm length of 0.15 m (0.5 feet) was built to provide a better match of bandwidths for the identification of the mine-like target. Mine identification is the subject of Chapter VII.

In the next chapter, we study the effects of target depth and size on the characterization and identification of subsurface targets.
CHAPTER VI
EFFECTS OF TARGET DEPTH AND SIZE ON THE CHARACTERIZATION AND IDENTIFICATION OF SUBSURFACE TARGETS

A. Introduction

To study the effects of target size and depth on the characterization and identification technique, two sets of targets were buried (see Figures 27 and 28). The first set consisted of a series of different-size brass cylinders buried at different depths. The second set consisted of a series of different-length 0.3125 cm (1/8-inch) diameter thin brass wires buried at the depth of 5 cm (2 inches). Backscattered waveforms were obtained using the subsurface pulse radar at various antenna locations. Locations of the antenna center are shown as dots in Figures 27 and 28.

B. Processed Waveforms

Processed waveforms from the cylinder and the wire targets are shown in Figures 29-31. From these waveforms, the following observations are made:

1. All these waveforms exhibited some transient behavior, signifying the possible existence of one or more natural resonances.

2. A comparison between the brass cylinder waveforms shown in Figures 9 and 29 indicates that the signal level of the waveform from the brass cylinder at 5 cm depth was approximately 12 dB higher than that of the waveform from the brass cylinder at 30 cm depth. This signified a propagation loss of over 10 dB per 30 cm (1 foot).

3. A burst of signal energy appeared in the early-time portion of the waveforms from the brass cylinders at 90 and 150 cm depth. This was caused by a phenomenon known as the "Trench effect"[22].

Rain, snow and evaporation changed the moisture content of the ground and the distribution of moisture was perturbed by the Trench walls. At times during the course of a year the ground in the trench was found by direct measurement to be drier and at other times wetter.
Figure 27. Layout of the buried cylinders.
Figure 28. Layout of the buried thin wires.

60 cm LONG THIN WIRE

15 cm

30 cm LONG THIN WIRE

ANTENNA ORIENTATION

45 cm LONG THIN WIRE

DEPTH OF ALL THIN WIRES 5 cm (2 INCHES)
DIAMETER OF ALL THIN WIRES = 0.31 cm (1/8 INCH)
Figure 29. Processed waveforms from the different-size cylinders at 30 cm depth.
Figure 30. Processed waveforms from the 300cm long cylinder at different depths.
Figure 31. Processed waveforms from the different-size thin wires at 5 cm depth.
than the ground outside the trench. Thus, the trench became a scatterer. The trench signal obscured the cylinder signal and made the task of target identification difficult.

4. Careful study of the waveforms of Figure 31 from the thin wires indicated that the time interval between zero crossings increased according to the increase in the wire size. Such phenomenon was not observed in the cylinder waveforms.

C. The Extracted Resonances

1. Effects of target depth

To see the effects of depth on the complex resonances, the average extracted resonance of the 30cm long cylinders at different depths are shown in Figure 32. From these resonances, we make the following observations:

a. The high-frequency content in the backscattered waveforms was highly attenuated as target depth increases. The highest-order resonance which was present in the 5 and 30cm deep cylinder waveforms was absent from the waveforms of the deeper cylinders.

b. All resonances with imaginary parts smaller than 400 MHz were present in the cylinder waveforms of all depths.

c. The lowest-order resonance was the antenna resonance (0.6m long antenna). This resonance was present in almost all the waveforms of all targets at all depths collected using this antenna.

d. The imaginary part of the target resonances of the brass cylinder occurred in integer multiples of the imaginary part of the lowest-order target resonance. This seemed to suggest that the extracted resonance of the brass cylinder were caused by the multiple scattering mechanisms along the length of the cylinder only (i.e., the dipole mode)[21], the creeping-wave modes were not present in the waveforms. The absence of the creeping wave type resonances was further emphasized when we compared the extracted resonances of the same-size thin wire at the depth of 5 cm to the cylinder resonances (see Figure 32). The same lower-order resonances were extracted. This proved the absence of the creeping-wave modes, for the creeping-wave modes of the thin wires have resonant frequencies which are too high to be present inside the bandwidth of our radar system. The absence of the creeping-wave modes is attributed to the high loss suffered by the creeping waves as it traveled around the circumference, and the cross-polarization effects of the crossed-dipole antenna system.
Figure 32. Average extracted resonances of the 30cm long cylinders at different depths.
With the absence of the creeping-wave type resonances, from the point of view of the target resonances, the thin wire and the cylinder are indistinguishable. Separation of these two targets is possible only when discriminants other than the lower resonances are used. One such possible discriminant is the forced response of the back-scattered waveforms which contains information about the profile area of the target[48].

e. The fact that the extracted resonances of the 30cm long cylinder are related solely to the length of the cylinder suggests the use of these resonances to estimate the parameters of the ground. If we consider these resonances to be an approximation to the resonances of the same-size cylinder in a homogeneous medium illuminated by a plane wave, the imaginary parts of these resonances can be approximated by Equation (54)[21]

\[ f_n = \frac{n - \frac{c}{2L}}{\sqrt{\varepsilon_r}} ; \quad n = 1, 2, 3, \ldots \]  

(54)

where \( L \) is the physical length of the cylinder, \( c \) is the speed of light in free space and \( \varepsilon_r \) is the relative dielectric constant of the medium. Using Equation (54) and the extracted resonances of the 30cm long cylinder as given in Figure 32 the relative dielectric constant is estimated to be approximately 20 at the resonant frequency of approximately 100 MHz. This estimate agrees closely with the estimate from other methods currently being investigated in the ElectroScience Laboratory[58].

The complex resonances of the 30cm long cylinders and thin wire relate very simply to their physical size. This simple relationship disappears when the size of the target increases beyond a certain threshold. This is demonstrated in the following discussion.

2. Effects of target size

As target size increases, we expect the target resonances to be lower in frequency. Such expectation turns out to be warranted when we consider the extracted resonances of the different-size thin wires at the depth of 5 cm as shown in Figure 33. Again, the imaginary parts of target resonances occur in simple multiples of the imaginary parts of the lowest-order target resonance, and as the length of the wire increases up to 60 cm, the frequency decreases according to its size. This expectation turns out to be unwarranted when the length of the cylinder increases to over 90 cm at the depth of 30 cm.
Figure 33. Average extracted resonances of the different-size thin wires at 5 cm depth.
Extracted resonances of the different-size cylinders at the depth of 30 cm are shown in Figure 34.

Although resonances of the large-size targets are no longer related to their sizes in simple form, however, there are still resonance present in the backscattered waveforms. Hence identification of these targets is still possible. Some identification results are presented in the next section.

Figure 34. Average extracted resonances of the different-size cylinders at 30 cm depth.
D. **Target Identification**

Some single-look identification performance results are given in Table 12. Based on these results, the following observations are made:

1. All false alarm probabilities were less than 8%. In some cases, estimates of $P_I=100\%$, $P_{FA}=0\%$ were obtained.

2. Identification range decreased as target depth increased.

In the next chapter we focus our attention on the detection and identification of mine-like targets in more extensive and practical situations. Improvements over the Terrascan-like pulse radar are made for the implementation of a portable on-location real-time sub-surface target identification radar.

| TABLE 12 |
| SUMMARY OF SINGLE-LOOK IDENTIFICATION PERFORMANCE |
| FOR THE BRASS CYLINDERS OF DIFFERENT SIZES |
| $P_I=100\%$ For All Cases |

<table>
<thead>
<tr>
<th>BRASS CYLINDER</th>
<th>$R_{ID}$ (cm)</th>
<th>$P_{FA}$ (%)</th>
<th>NUMBER OF WAVEFORMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>South-North</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>30</td>
<td>3.08%</td>
</tr>
<tr>
<td>90</td>
<td>30</td>
<td>60</td>
<td>7.25%</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>105</td>
<td>0%</td>
</tr>
<tr>
<td>300</td>
<td>30</td>
<td>150</td>
<td>0%</td>
</tr>
<tr>
<td>300</td>
<td>90</td>
<td>150</td>
<td>7.9%</td>
</tr>
<tr>
<td>300</td>
<td>150</td>
<td>150</td>
<td>0%</td>
</tr>
</tbody>
</table>

*See Figure 27.*
CHAPTER VII
ELECTROMAGNETIC MINE DETECTION AND IDENTIFICATION

A. Objectives

This chapter focuses on the detection and identification of mine-like targets. First, a second model of the mine-like target was buried at the same depth of 5 cm. Measurements were obtained over the two isolated mine-like targets for comparison and identification. Second, to simulate a realistic mine identification situation, a set of waveforms was obtained over a section of a rough road in which numerous false targets existed. These false targets were caused by the debris existing in the old country-style road, and thus represented a set of realistic false targets in a mine field. The set of rough road measurement was used for evaluation of "typical" false-target discrimination. Third, a small antenna of arm length 0.15 m (0.5 foot) was built and used to provide better characterization and identification of the mine-like target. Performance of the small-antenna system is presented and discussed.

B. A Second Model of the Mine-Like Target

Typical processed waveforms from the two mine-like targets at the same relative antenna-target geometry are shown in Figure 35. There are minor differences in these two waveforms. This can be attributed to the minor difference in the structure of these two targets, clutter and the difference in the ground conditions at the two target locations. Complex natural resonances of the two models of the mine-like target were extracted from their backscattered waveforms using Prony's method. The average extracted resonances of the two models are shown in Figure 3b. Again the slight difference in the locations of these two sets of resonance is attributed to the possible slight difference in the structure of the two models, clutter and the difference in the ground conditions at the two target sites.

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Figure 35. Processed waveforms from the two models of the mine-like target.
Figure 36. Average extracted resonances of the two mine-like targets.
C. False Target Measurements in the Rough Road

A set of 53 (difference) waveforms was collected over 53 locations in a 40m section of a rough road adjacent to the Electro-Science Laboratory. These echoes were probably a result of debris existing in this old country-style road. There were numerous such false targets observed. Pictures of the rough road is shown in Figure 38.

The measurement locations were chosen to ensure significant false-target signal levels for a more realistic and difficult test of the identification method. Figure 38 shows a typical false-target waveform.

D. Mine Identification

The predictor-correlator identification method was applied to the waveforms from the two mine-like targets and the rough road-bed for identification of the two mine-like targets and false-target discrimination. Single-look identification statistics are given in Table 13.

This set of identification statistics basically established the fact that the predictor-correlator identification method did indeed successfully identify different models of the mine-like target at different locations. Furthermore, the method successfully separated the mine-like target from the set of false targets which were typical of the false targets found in a realistic mine field.

The pulse radar system discussed so far represented a workable (and successful) mine identification system, however two obvious improvements could be made. First, there was the bandwidth mismatch problem (as discussed in Chapter V) that resulted in low-level values of the correlation coefficient. The bandwidth mismatch problem could be corrected by introducing an antenna system with a higher-frequency antenna resonance. Second, the size of the crossed-dipole antenna (1.2 m (4 feet) maximum dimension) was a bit too large for a practical mine identification system. There existed a single solution to the two problems mentioned above. This solution was the reduction in the antenna size. Since the 0.6m long (arm length) antenna had a resonance at 65 MHz, a 0.15m (0.5 foot) long antenna would have a resonance at 260 MHz which was close to the mid-frequency of the resonance bandwidth. A crossed-dipole of 0.15 m arm length was therefore built for improved mine identification performance[59]. Performance of this antenna on the identification of the mine-like target is discussed in the next section.
Figure 37. The rough road for false-target measurements.
Figure 38. Processed waveform from a typical false target in the rough road.
TABLE 13
SINGLE-LOOK IDENTIFICATION STATISTICS: THE FIRST AND SECOND MODEL OF THE MINE-LIKE TARGET VS THE FALSE TARGETS IN THE ROUGH ROAD-BED. 

<table>
<thead>
<tr>
<th>DESIRED TARGET</th>
<th>GROUND CONDITION</th>
<th>T_{oi}</th>
<th>T_{Hi}</th>
<th>T_{Ha}</th>
<th>R_{ID}</th>
<th>P_{FA}</th>
<th>DESIRED TARGET</th>
<th>UNDESIRED TARGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET WET,1</td>
<td>FIRST MODEL</td>
<td>4T_B</td>
<td>.948</td>
<td></td>
<td></td>
<td>.25937</td>
<td>30</td>
<td>1.85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5T_B</td>
<td>.667</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6T_B</td>
<td>-.209</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7T_B</td>
<td>.243</td>
<td></td>
<td></td>
<td>.667</td>
<td>30</td>
<td>1.85%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8T_B</td>
<td>-.0615</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>9T_B</td>
<td>-.118</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10T_B</td>
<td>.224</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MINE-LIKE TARGET WET,2</td>
<td>SECOND MODEL</td>
<td>5T_B</td>
<td>.445</td>
<td></td>
<td></td>
<td>.30050</td>
<td>30</td>
<td>3.70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6T_B</td>
<td>-.488</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7T_B</td>
<td>.127</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8T_B</td>
<td>.243</td>
<td></td>
<td></td>
<td>.30050</td>
<td>30</td>
<td>3.70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9T_B</td>
<td>.289</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10T_B</td>
<td>.221</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>11T_B</td>
<td>.436</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12T_B</td>
<td>-.259</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
E. A Small Antenna for Improved Performance in Mine Identification

A picture of the small crossed-dipole antenna is shown in Figure 39. This antenna was used to obtain a set of measurements over the 5cm deep targets. Typical processed waveforms are shown in Figure 40. For comparison purposes, Figure 41 shows the processed waveforms obtained using the 0.6m long antenna over the same target locations. From Figures 40 and 41, we note the following improvements obtained using the 0.15m long antenna. First, the 0.15m long antenna offers a gain of at least 6 dB in target signal level. Second, the level of the no-target signal obtained using the 0.15m long antenna is generally lower. Third, the time interval of the target signals obtained using the 0.15m long antenna is only half as long. This reduction in interval size would effectively reduce the computation time for evaluating the correlation coefficient by a factor of two.

Due to the minimization of the length of the inter-connecting cables at the balun-antenna connection of the small antenna, the balun reflection exists in the early-time portion of the waveform. In this region, the primary target signal level is much higher than the level of the balun reflection. This severely suppresses the effects of the balun reflection. The decrease in cable length is also a contributing factor to the 6 dB gain in signal level. With the balun reflection moved in, the stop-time $t_e$ of the error-calculating interval in the Prony's and the predictor-correlator identification processes had to be changed. In this study, the choice of $t_e$ for the small-antenna system was based on the resonances of the mine-like target. The value of $t_e$ was chosen to yield an error interval of size equal to five times the period of the lowest imaginary part of the target resonances (125 MHz). This resulted in the $t_e$ value of $t_s+100f_0$.

Figures 42-44 show more waveforms and their FFT's obtained using the 0.15m long antenna. From the FFT's of the waveforms, it is found that most energy resided in the frequency region of 100 MHz to 500 MHz with the most dominant frequency in the region of about 300 MHz (as compared to 70 MHz for the 0.6m long antenna).

The set of waveforms obtained with the small antenna over the 5cm deep targets was processed for pole extraction and identification of the mine-like target. Average complex resonances of the mine-like target extracted from these waveforms are shown in Figure 45. For comparison purposes, the extracted resonances from the mine-like target waveforms obtained with the 0.6m long antenna in a similar ground condition are also shown in Figure 45. The locations of the target resonances from both antennas were almost identical. However, the imaginary part of the antenna resonance increased by a factor of 4 when the length of the antenna arm was reduced from 0.6 m to 0.15 m.
Figure 39. The small crossed-dipole antenna for improved mine identification performance.
Figure 40. Processed small-antenna waveforms from the 5cm deep subsurface targets.
Figure 41. Processed waveforms from 5cm deep targets measured using the 0.6m long antenna.
Figure 42. Additional processed small-antenna waveforms from the 5cm deep targets.
Figure 43. FFT of the small-antenna waveforms shown in Figure 40.
Figure 44. FFT of the small-antenna waveforms shown in Figure 42.
Figure 45. Average extracted resonances from the mine-like target waveforms taken using the 0.15m and the 0.6m long antennas in similar ground conditions.
Complex resonances of the various 5 cm deep targets are shown in Figure 46. The antenna resonance was present in almost all target waveforms measured. The complex resonances of these targets were in the same general area of the complex frequency plane as the antenna resonance. This was expected to present a difficult test to the identifier.

Single-look identification statistics obtained using the small antenna in identification of the mine-like target is shown in Table 14. Typical \( \nu(T) \) curves are shown in Figure 47. From Table 14 and Figure 47, the following observations are made:

1. Target identification performance estimates based on the extracted resonances of the mine-like target was \( P_I = 100\% \), \( P_{FA} = 1.72\% \) within a 30 cm radius of target center. Within a 45 cm radius, identification performance was \( P_I = 100\% \), \( P_{FA} = 6.90\% \). This set of statistics was obtained with an ensemble of 13 mine-like target and 58 false-target waveforms. These performances represented an improvement over the performance obtainable with the 0.6 m long antenna. The 0.6 m long antenna system was unable to identify the mine-like target in a distance of more than 30 cm from the target center.

2. In addition to the range improvement, a quick comparison between the identification statistics given in Tables 8 and 14 indicates that the level of \( \nu(T) \) values for the mine-like target were generally improved. It is expected that this will produce improved identification in the presence of greater amounts of clutter. It has already been observed that target identification in the presence of clutter has been improved.

3. The region of \( T_0 \) values for optimum identification performance was in the neighborhood of \( T_0 = 6 T_B \). However, this region of \( T_0 \) values was shifted towards small \( T_0 \) values. This was attributed to the shift to dominance of the high-frequency poles due to the shift in the antenna resonance. Note that the region of \( T_0 \) included \( T_N \).

Because of the change in the bandwidth of the small-antenna system a band-pass filter was used in the preprocessor of the identifier to suppress out-of-band clutter and noise. The transfer function of the band-pass filter is shown in Figure 48.

In the next chapter, we discuss the implementation of the small-antenna mine identification system as a microcomputer system. Target identification performance will be given.
Figure 46. Average extracted resonances from the waveforms of the 5cm deep targets obtained with the small antenna.
TABLE 14
SINGLE-LOOK IDENTIFICATION PERFORMANCE FOR IDENTIFICATION
OF THE MINE-LIKE TARGET WITH THE SMALL-ANTENNA SYSTEM.
$P_1 = 100\%$

<table>
<thead>
<tr>
<th>DESIRED TARGET</th>
<th>GROUND CONDITION</th>
<th>$o_i$</th>
<th>$\Phi_i$</th>
<th>$\Phi_A$</th>
<th>$P_{FA}$</th>
<th>$P_{FA}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R$_{ID}$=30 cm</td>
<td>R$_{ID}$=45 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MINE-LIKE TARGET</td>
<td>WET</td>
<td>4TB</td>
<td>.615</td>
<td>.59436</td>
<td>1.72%</td>
<td>6.90%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5TB</td>
<td>.166</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6TB</td>
<td>.615</td>
<td>.456</td>
<td>.420</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>7TB</td>
<td>.59436</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8TB</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NUMBER OF WAVEFORMS</th>
<th>DESIRED TARGET</th>
<th>UNDESIRED TARGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>R$_{ID}$=30 cm</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>R$_{ID}$=45 cm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 47. Typical $\rho(T)$ curves for the identification of the mine-like target using the small-antenna system.

Figure 48. Transfer function of the preprocessor filter used in the small-antenna system for target identification.
CHAPTER VIII
A MICROCOMPUTER SYSTEM FOR REAL-TIME ON-LOCATION SUBSURFACE TARGET IDENTIFICATION

A. Objectives

This chapter discusses the implementation of the pulse radar identification system as a microcomputer system for real-time on-location identification of subsurface targets. The identification radar is implemented with an SDK-80 microcomputer[60] in conjunction with the Terrascan. The processing algorithms are stored in the system as microprograms. Arithmetic operations are performed by a hardware arithmetic processing unit and data can be recorded by a cassette recorder. Thus the microcomputer system can serve either as a real-time identification system or as a data-recording system.

B. Structure of the Microcomputer Target Identification System

The basic structure of the microcomputer target identification system is shown in Figure 49. The major components and their corresponding functions are the following:

1. Terrascan System: the raw backscattered waveform is received by the crossed-dipole antenna in analog form. This analog waveform is sampled by the Terrascan system which essentially serves as a sampling oscilloscope and provides various flexibilities such as gain, time delay, and dc offset to the waveform. The sampled raw waveform is displayed on the neon display and then fed to the analog board as a discrete-time signal.

2. Analog Board: besides converting the sampled raw waveform to digital form using an 8-bit A/D converter, the analog board provides a keyboard for inputting to the microcomputer system. Various operating modes of the microcomputer system are initiated through the command codes entered from the keyboard. The analog board also provides 6 LED display lights for displaying echoes of the input command codes, various system operating information, and important
Figure 49. Block diagram of the microcomputer system for un-location subsurface target identification in real time.

information concerning the received waveform (such as peak timing, peak values, etc.).

3. SDK-80: this is the microcomputer unit. All operating system programs, signal-preprocessing, detection and identification and data-recording operations are stored as microprograms in the SDK-80[60]. These microprograms are executed when the proper commands are entered from the keyboard. The SDK-80 is an 8-bit machine running at a clock rate of 2 MHz.

4. Arithmetic Processing Unit (APU): the hardware arithmetic processing unit is interfaced to the SDK-80 microcomputer for high-speed arithmetic calculations. The APU provides various flexibilities such as floating-point or fixed-point arithmetic, single or double precision, function (such as trigonometric functions, etc.) generations, etc.
5. **Memory Board:** 8K memory bytes (8 bits/byte) for data storage.

6. **Cassette Recorder:** used for data recording

Similar systems had been built and documented under different studies[67] at the ElectroScience Laboratory. Except for the addition of the hardware arithmetic processing unit, the system developed and implemented in this dissertation has basically the same design and hardware. Thus, only the details concerning the APU are given in Appendix I. Details concerning the other modules of the microcomputer system are well documented in various reports[67].

C. **Implementation of the Microcomputer System for Subsurface Target Identification**

Pictures of the microcomputer system and its components are shown in Figures 50 and 51. Two major operations, namely target identification and data recording were implemented in the microcomputer system. The target identification process performed by the microcomputer is outlined in Figure 52. All processes except the automatic tuning process have been implemented. The tuning process is discussed in Chapter IX. In short, when the target identification mode is being executed, the Terrascan samples the received analog waveform, displays and feeds it to the analog board for A/D conversion. The digital waveform is then fed to the memory board where the average waveform is formed. The average waveform goes to the preprocessing unit for reduction in clutter/noise. This preprocessed waveform arrives at the detector for a screening operation. The detector screens out waveforms whose energy, peak timing and peak amplitude are out of the desired ranges. The "in-range" waveform would then be fed to the predictor-correlator for target identification. "Out-of-range" waveforms are considered as "undesired-target" waveforms. The correlation coefficients and the processed waveforms are stored in the 8K memory which is transferred to the cassette recorder when filled. For target identification based on the predictor-correlator method, only the difference equation coefficients corresponding to the desired target need to be stored in the microcomputer for the evaluation of p(T), the complex resonances are not stored. For multiple-threshold identification, a set of coefficients corresponding to each chosen value of Toi needs to be stored. Note that these coefficients depend on ground condition, thus, for on-location subsurface target identification in real time, an automatic tuning process is necessary. Automatic tuning of the identification radar to the ground condition is discussed in Chapter IX.

A list of executable commands and their detailed descriptions are given in Table 31 of Appendix I.
Figure 51. The microcomputer and its components.
Figure 51 (cont'd). The microcomputer and its components.
Figure 52. The identification process implemented in the microcomputer system.
The following notes with regard to the implementation of the microcomputer identification system are important:

1. Due to hardware constraints in the Terrascan, a waveform obtained with the microcomputer system contained only 128 data points. The waveforms obtained with the digital computer controlled system contained 256 data points. Thus, we were faced with possible loss of resolution in time (i.e., a larger sampling period must be used in order for 128 samples to cover a 50 ns time window) or frequency (i.e., smaller time window must be used). Careful study of the small-antenna waveforms from the mine-like target revealed the fact that the energy of practically all waveforms resided in a time window of 25 ns (see Figure 40). Hence, by choosing a time window for 25 ns and 128 samples for the mine identifier, both time and frequency resolution were maintained.

2. Besides frequency and time resolution of the waveforms, the other important considerations are data precision, flexibility and speed. In this system, double-precision floating-point* arithmetic is used to perform the major calculations such as the evaluation of the correlation coefficient $\rho(T)$ and the FIR filtering in the preprocessing unit. The floating-point format offers large dynamic range, flexibility and ease of implementation. The function-generation capability (such as trigonometric functions, transcendental functions, etc., are available for floating-point numbers only) of the APL provides tremendous flexibilities in the implementation of digital signal processing techniques. These, together with the fact that scaling operation is not needed for floating-point operations, makes the floating-point format an ideal choice for a "first-generation" computer system. The tremendous amount of scaling operations in the fixed-point calculations makes the calculations difficult to track and furthermore, the great amount of scaling often causes loss in data precision. The trade-off in using the floating-point format is the computing speed. Floating-point operations usually take more computing time than the corresponding fixed-point operations. Furthermore, the 25-bit mantissa offers less "nominal" data precision than the 32-bit fixed-point formatted number. With the choice of data format, we now estimate the computing time needed for an identification decision. The major areas requiring significant amount of computations are the following:

*Floating-point number in this system is represented by a 7-bit exponent and a 25-bit mantissa.
a. Arithmetic averaging

This process forms the arithmetic average of $N_1$ raw waveforms from the same antenna location and orientation for reduction of noise. Here, the major part of the computation time goes to the sampling of the $N_1$ waveforms. The sampling time $\Delta t$ is inversely proportional to the repetition frequency of the radar source, i.e., the impulse generator, and

$$\Delta t = \frac{N_1 \cdot N_2}{R_F}$$

where

$N_1$ = number of waveforms required to form the average,

$N_2$ = number of samples in a waveform, and

$R_F$ = repetition frequency of the impulse generator.

In the present system, $N_1=10$, $N_2=128$ and $R_F=256$. Thus $\Delta t=5$ seconds. If the repetition frequency can be increased to 10 KHz*, $\Delta t$ will be decreased to 0.125 second.

b. 90°-difference

This process forms the difference between two waveforms from two antenna orientations (one of which is a 90° rotation from the other) at the same antenna location. The differencing operation basically increases the sampling time by a factor of 2. In the final system applications, this process is probably not needed. At any rate, the antenna rotation process will represent a major time factor.

c. Calculation of $\rho(T)$

This process evaluates the correlation coefficient $\rho(T)$ at all chosen values of $T_0$'s for multiple-threshold identification. Note that with the choice of floating-point format, the expression for $\rho(T)$ given in Equation (24) can be manipulated for minimum computation time. In floating-point calculations, due to the shifting of exponents required for the add/subtract operations, the amount of time required to perform an add/subtract operation can be larger than that required for a multiply/divide operation. Table 15 lists the computation time required by the APU to perform each of the four basic floating-point arithmetic operations. The maximum difference in the average computation time for the four operations are less than 23% of the minimum

*This is believed to be within state-of-the-art technology.
TABLE 15
COMPUTATION TIME REQUIRED BY THE APU TO PERFORM THE FLOATING-POINT ARITHMETIC OPERATIONS

<table>
<thead>
<tr>
<th>FLOATING POINT OPERATION</th>
<th>MINIMUM</th>
<th>MAXIMUM</th>
<th>AVERAGE**</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD</td>
<td>56</td>
<td>350</td>
<td>203</td>
</tr>
<tr>
<td>SUBTRACT</td>
<td>58</td>
<td>352</td>
<td>205</td>
</tr>
<tr>
<td>MULTIPLY</td>
<td>168</td>
<td>168</td>
<td>168</td>
</tr>
<tr>
<td>DIVIDE</td>
<td>171</td>
<td>171</td>
<td>171</td>
</tr>
</tbody>
</table>

* 1 clock cycle = 500 ns
**AVERAGE = (MINIMUM+MAXIMUM)/2

average computation time. Thus it seems reasonable to manipulate the expression for \( \mu(T) \) to minimize the total number of operations. Based on the above criterion, the following expression for \( \mu(T) \) is implemented in the predictor-correlator of the microcomputer system for target identification.

\[
\mu(T) = 1 - \frac{t_c - NT + m_o T}{t = t_s + m_o T} \left( \sum_{t = t_s + m_o T}^{t_c - NT + m_o T} e^2(t) + \sum_{t = t_s + m_o T}^{t_c - NT + m_o T} \left( r_M(t)(r_M(t) - e(t)) \right) \right)
\]

(56)

where

\[ e(t) = r_M(t) - r_C(t) \]

The number of arithmetic operations required to evaluate \( \mu(T) \) at a \( T \) value of \( T_0 \) is given in Table 16.
In Table 16,

\[ N = \text{number of resonances of the desired target used for identification purposes}, \]

\[ M = \frac{(t_e - t_s + T_B)}{T_B}, \quad \text{and} \]

\[ I_{01} = \frac{T_{01}}{T_B}. \]

Note that \( M - N I_{01} \) is the number of instantaneous error samples in the error interval.

With the small antenna system and for mine identification, \( N = 10, M = 101, I_{01} = 4, 5, 6, 7 \) and 8 (see Chapter VII). The total computation time ranges from 0.26 seconds to 0.64 seconds with an average of 0.45 seconds.

d. The filtering operation in the preprocessor

Because of the unavailability of the FFT package in the microcomputer system, the digital filtering operation in the preprocessor was performed in the time domain via the following relationship[55,56]

\[ r_M(nT_B) = \sum_{i=1}^{N'} h(iT_B) r_1(nT_B - iT_B) \]

(57)

where
$r_M(nT_B) =$ the processed filtered waveform,

$r_1(nT_B) =$ the processed unfiltered waveform,

$h(iT_B) =$ impulse response of the digital filter, and

$N' =$ order of the digital filter.

The impulse response of the digital bandpass filter given in Figure 47 was obtained by taking the inverse FFT of the digital filter transfer function. This impulse response and transfer function are shown in Figures 53a and b, respectively. Using this time-domain filter, a set of identification results was obtained using the in-house computer for the identification of the mine-like target based on the small-antenna waveforms previously obtained (see Chapter VII). Identical estimates of identification performance were obtained (i.e., $P_1=100\%$, $P_{FA}=1.72\%$ for $R_{ID}=30$ cm, and $P_1=100\%$, $P_{FA}=6.90\%$ for $R_{ID}=45$ cm).

The time-domain filter shown in Figure 53b is a FIR filter with a large order of $N'=128$. Thus, tremendous computation time will be consumed in the filtering operation if it is to be implemented in the microcomputer system. To save computation time, the order of this FIR filter was lowered to 37 by using a "windowing" technique with a Kaiser window[55,56,61]. The Kaiser window, the "windowed" impulse response of the filter and the FFT of the windowed impulse response are shown in Figure 53c-e. Identification performance estimates obtained using the in-house computer with this windowed filter was $P_1=100\%$, $P_{FA}=8.62\%$ for $R_{ID}=45$ cm. Thus, performance only slightly degraded. This filter was incorporated into the microcomputer system for real-time identification of the mine-like target. The windowed time-domain filter has 37 coefficients and is symmetric about its center. Based on Equation (57) and Table 15, the average time required for the filtering operation on a small-antenna waveform is 0.5 seconds (vs 2 seconds for the unwindowed filter). The digital filter can be replaced by an analog filter placed at the front end of the receiver in the final identification system.

e. Detection

Operations performed in the detection include peak detection, energy calculations, etc.

f. Execution of computer instructions

The amount of time taken for execution of the computer instructions depends on the efficiency of the microprogram written.

In summarizing, the amount of time required for an identification decision in the identification of the mine-like target with the existing small-antenna microcomputer system is estimated to be approximately 11 seconds with 0.45 seconds of average predictor-correlating time.
Figure 53. Design of the preprocessor FIR filter for target identification with the small-antenna microcomputer system.
The decision time goes down drastically to about 0.7 seconds if the repetition frequency of the pulser can be increased to 10 KHz, and the filtering operation in the preprocessor can be performed with an analog filter. Using state-of-the-art technology, both these conditions can be easily met.

Based on the simulated identification results obtained with the microcomputer conditions (i.e., 128 samples per waveform, FIR filtering), the microcomputer identification system is expected to identify the mine-like target with the same level of performance as the results previously presented in this dissertation.

D. Calibration of the Microcomputer

Target Identification System

Calibration of the microcomputer system includes the following:

1. **Time scale**

   The time scale was calibrated by comparing two waveforms from the same target. One of the waveforms was obtained with a fixed length of cable added to the system. The time window was calibrated at 25 ns. However, the impedance mismatch at the trigger pick-off circuitry of the Terras-an limited the reflectionless time window to 20 ns (see Figure 54). The secondary reflections caused by this impedance mismatch occurred at a time which was 20 ns from the transmit-receive coupling. This reduction in the size of the reflectionless time window was later found to limit the identification range of the radar system.

2. **Amplitude scale**

   Operations performed in the detector required accurate calibration of the peak amplitude, peak timing as well as the energy of the mine-like target waveforms. These calibrations were performed by collecting a set of waveforms over the mine-like target and tabulating the various detection thresholds based on the set of waveforms.

3. **On-location ground condition**

   On-location ground-condition calibration is discussed in Chapter IX. At the present time, the in-situ complex resonances of the mine-like target waveforms were obtained by analyzing the waveforms collected in § using Prony's method. The difference equation coefficients associated with these resonances were then used for real-time target identification. Real-time identification performance of the microcomputer system is discussed in the next section.
Figure 54. Typical processed mine-like target waveform received by the microcomputer system.
E. Real-Time Identification Performance of the Microcomputer Target Identification System

1. Identification performance

Two sets of identification data were obtained for the identification of the mine-like target in two different ground conditions. The first set was obtained using the poles and thresholds as given in Tables 27 and 30 of Appendix G for real-time identification of the mine-like target. Real-time identification performance of $P_I=100\%$ and $P_{FA}=0\%$ was obtained for $R_{ID}=30\text{ cm}$ (based on 9 mine-like target waveforms and 21 other-target waveforms). It was found that, for $R_{ID}=45\text{ cm}$ identification performance degraded to $P_I=12\%$, $P_{FA}=0\%$. This reduction in identification range was attributed to the presence of the unwanted reflections from the trigger pick-off in the latter portion of the time window.

The second set of identification data was obtained under a different and rapidly changing ground condition. A set of measurements over the mine-like target was collected over a lightly wet ground for calibrating the ground condition, target resonances, and the various detection and identification thresholds. However, there were rapid weather changes between the time of data analysis (for calibrations) and real-time identification. There was heavy rainfall during the interim period, and in one day, even a moderate snow storm. These drastic weather changes altered the ground condition, and with the system tuned to the previously calibrated conditions, it was found that the level of the correlation coefficients for the mine-like target waveforms was generally lowered. Hence to ensure a 100\% identification probability, the identification thresholds had to be lowered. Thus, with an untuned system and using lower threshold values (see Appendix I for details), a set of real-time identification data was obtained. Identification data based on 17 mine-like target and 13 other-target waveforms were $P_I=100\%$ and $P_{FA}=0\%$ for $R_{ID}=30\text{ cm}$. Thus, lowering the threshold values seems to be an effective means to counter the problem of uncertain ground conditions for this penetrable "desired target". This aspect of the system warrants a detailed future investigation.

2. Speed

The two sets of identification data discussed in the above subsection were obtained with $N_1$ (the number of raw waveforms required to form an average waveform) set equal to 8. Thus, for a pulse repetition rate of 256 Hz, the amount of time required for the microcomputer system to form an average difference waveform was 8 seconds. The amount of time taken for the correct identification of the mine-like target was clocked at approximately 2.5 seconds. Thus, the total real-time for a correct identification of the mine-like target was approximately $10.5\text{ seconds}$. The amount of time required for false-target or no-target discrimination was less than $10.5\text{ seconds}$. In the
Implementation of later generations of this identification system, it is expected that, the identification speed will drastically increase with the increase in pulse repetition rate, decrease in Np, elimination of the 90° difference operation, and more efficient microprograms.

3. Precision

To find the precision of the correlation coefficients calculated in the microcomputer system, correlation coefficients were calculated for a waveform using the microcomputer system. These correlation coefficients were then compared to those calculated by the in-house computer system for the same waveform. It was found that, the two sets of results differed in the 10th bit of the mantissa of the floating-point formatted numbers. No error was observed in the exponents. Thus, using the 25-bit floating-point format of the APU resulted in a 0.1% truncated error in the correlation coefficients. This is expected to have little effect on the identification performance.

F. Possible Future Improvements on the Microcomputer System

In addition to the impedance mismatch at the trigger pick-off circuitry of the Terrascan, a few other aspects of the microcomputer system can be modified to improve identification performance.

1. The sampling system in the Terrascan

The Terrascan system was originally designed for low-frequency operation (i.e., frequencies less than 200 MHz), as such its sampling system is therefore slow. The slow sampling system causes loss in high-frequency content of the received waveforms. Figure 55 shows two waveforms, one received by the Terrascan and the other by a faster sampling system, from the same target at the same antenna location and orientation. The loss of high-frequency content in the waveform received by the Terrascan system is quite apparent.

With the identification performance obtained thus far using the microcomputer system, the high-frequency loss in the Terrascan sampling system does not seem to affect identification performance for the identification of the mine-like target considered in this study. However, such high-frequency loss will almost surely degrade performance when the system is used to identify smaller mines.

2. The dynamic range in signal level

The microcomputer system currently uses an 8-bit A/D converter to convert the received analog waveforms to digital form. This results in a 48 dB dynamic range in signal level. For the identification of low-level signals the dynamic range needs to be increased.
Figure 55. Processed mine-like target waveforms received by the microcomputer and the fast sampling system.
3. **Gain control of the Terrascan**

The gain control of the Terrascan system offers a limited range of gains in large discrete steps. Such large discrete steps may result in large truncation error.

In summarizing, a microcomputer system has been implemented for real-time subsurface target identification. Real-time single-look identification performance of \( P_I = 100\% \) and \( P_{FA} = 0\% \) for \( RID = 30 \) cm was obtained with a total of 26 mine-like target waveforms and 34 other-target waveforms for the identification of the mine-like target in different ground conditions. The amount of time required for a correct identification of the mine-like target was approximately 10.5 seconds. The amount of time required for a correct other-target or no-target discrimination was less than 10.5 seconds.

The microcomputer system built in this study was intended to be a "first-generation" system. Many possible modifications of the system were recommended in this chapter for better identification speed, data precision, and identification performance. The most important modification is the process of automatic tuning of the radar system to the on-location ground condition. This is the topic of Chapter IX.
CHAPTER IX
A METHOD FOR REAL-TIME ON-LOCATION TUNING OF THE IDENTIFICATION RADAR TO THE GROUND CONDITION

A. Objectives

The importance of tuning the radar system to the ground condition was illustrated in Chapter IV. An un-tuned subsurface identification radar system yielded degraded performance. This chapter discusses a possible method for automatic tuning of the radar system to the ground condition. Emphasis is on the simplicity of the method and the possibility of incorporation such method into the microcomputer system for on-location target identification in real time.

B. The Use of Backscattered Waveforms From Thin Wires to Estimate The Ground Parameters

The backscattered waveforms from the buried thin wires as shown in Chapter VII possess the following properties which are useful in the calibration of ground conditions:

1. The waveforms contain complex natural resonances which are related to the ground parameters in a simple fashion.

2. The wire waveforms are of high amplitude, thus the estimate of the resonances will be accurate.

3. The lowest-order target resonance of the thin wires are the most dominant. (See Appendix J). This implies that the thin wire waveforms can be closely characterized by a single resonance. Thus,

\[ r_M(t) = 2a_1 e^{\pi_1(t-t')} \cos \omega_1(t-t') \]  \hspace{1cm} (58)

where

\[ r_M(t) = \text{processed waveform} \]

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\[ s_1 = \alpha_1 + j\omega_1 \text{ complex resonance,} \]

\[ \alpha_1 \text{ residue associated with } s_1, \text{ and} \]

\[ t' = \text{start time of the transient signal from the wire.} \]

For a thin wire, the first resonance can be approximated by Equation (58)

\[ \omega_1 = -\frac{\sigma}{2\varepsilon} - 0.0828 \frac{\nu_r L}{\sqrt{\varepsilon} \nu_r L} \]  

\[ \omega_1 = 0.9251 \frac{\nu_c}{\nu_r L} \]

where

\[ \sigma = \text{ground conductivity (homogeneous medium assumed),} \]

\[ \varepsilon = \text{ground permittivity,} \]

\[ c = \text{speed of light in free space,} \]

\[ \nu_r = \text{relative dielectric constant of the ground, and} \]

\[ L = \text{length of wire.} \]

The complex natural resonance given by Equation (59) is a good approximation to the first natural mode of a thin wire with a length/diameter ratio of 100 buried in a homogeneous medium of good dielectric (i.e., medium with a small loss tangent of \( \alpha/\omega < 1 \))[52,69]. Here, it is used to estimate the ground parameters based on the waveforms from the buried thin wires and is found to yield reasonable results.

Since the waveform is dominated by a single resonance, the values of \( \omega_1 \) and \( \omega_1 \) can be easily estimated from the decaying envelope and the peak timing at two samples of the waveform, thus, the ground parameters can be estimated via the following equations:

\[ r' = \left[ \frac{0.9251(t_1-t_0)c}{2L^{1/2}} \right]^2 \]

and

\[ \sigma = 2\left[ (t_1-t_0)^{-1} \ln \frac{r(t_1)}{r(t_0)} - 0.0828 \frac{\nu_c}{\nu_r L} \right] \]
where \( r(t_0) \) and \( r(t_f) \) are the sample values of the measured waveform at time \( t_0 \) and \( t_f \), respectively.* All other parameters are as previously defined.

Using Equation (60), the ground parameters represented by the waveform shown in Figure 56 are estimated to be \( \rho = 14 \) and \( \sigma = 24 \) mS/m.** These estimates are found to be very close to the estimates obtained using different techniques currently being investigated in another study at the ElectroScience Laboratory[58]. The method outlined in Equation (60) is attractive, for it uniquely characterizes the ground condition by two sample values of a thin-wire waveform.

C. Automatic Tuning of the Identification Radar to the Ground Condition

The knowledge of the ground parameters basically solves the automatic ground-condition tuning problem for the real-time identification of simple targets such as the brass cylinder and the aluminum sphere whose resonances are related to the ground parameters in a known analytical fashion[21,63]. However, it does not solve the tuning problem for the real-time identification of plastic mines, for the analytic relations between the complex natural resonances of the plastic mine-like target and the ground parameters are not known. To date, the characterization of targets, should it be free-space or subsurface targets, is a relatively new research problem. Furthermore, research efforts have mostly been concentrated in the characterization of perfectly conducting targets only. Characterization of dielectric targets such as the plastic mine-like target with complex natural resonances via analytical method has not been previously treated. This could be achieved but it represents a substantial research effort beyond the scope of the present study. In this study we suggest solving the automatic tuning problem for identification of mines experimentally with the procedure outlined as follows:

Step 1: Estimate the ground parameter by using the method outlined by Equation (60).

---

* Equation (60) is valid only when \( r_M(t_0) \) and \( r_M(t_f) \) are both non-zero and that \( \omega_1(t_f - t_0) = 2\pi n \) where \( n = 1, 2, 3, \ldots \).

** Note that these estimates are, of course, accurate only at \( \omega_1 \). Furthermore, the loss tangent, based on the estimated values of \( \rho \) and \( \sigma \), is found to be 0.252.
Figure 5C. A waveform from a buried thin wire for calibration of the ground parameters.
Step 2: Determine the loci of the complex resonances of the mine-like target experimentally as the ground parameters vary. Ground parameters can be controlled by using different kinds of soils, or by increasing the moisture and salt content of the ground. Thus, the loci of the natural resonances (or the coefficients $a_n$) can be determined as a function of $t_1-t_0$, $r_M(t_0)$, and $r_M(t_1)$ and stored in ROM's in the microcomputer identification system for on-location target identification in real time.

To make the above method even more attractive and practical, the thin wire does not have to be buried for ground-condition characterization. Figure 57 shows waveforms obtained from a thin wire laying at different locations on the surface of the ground.* Again, the waveform is dominated by one (pair) resonance and thus, the ground condition is uniquely characterized by the values and timing of two sample points of the waveform. In the case of the on-surface wire however, because of the fact that part of the wire is in the air, the ground parameters are no longer estimated accurately by Equation (60). Nevertheless, the unique information about the ground condition is assumed to be contained in the two samples of the waveform. Thus far, this assumption is found to be valid. The on-surface wire waveforms given in Figure 55 indicate different decaying envelopes and zero-crossing intervals for different ground conditions.

The method of ground-condition tuning outlined above amounts to an extensive experimental effort and is planned for the future.

---

* The wire has to be in good contact with the ground.
Figure 57. Waveforms from an on-surface thin wire (30 cm long) for automatic tuning of the subsurface radar to ground condition.
CHAPTER X
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. Summary

At the time research in this report was initiated, the claim that electromagnetic signals were impractical for subsurface exploration because of attenuation had already been refuted. References in this report contain additional evidence refuting this claim. We demonstrate that the received signals from objects beneath the surface of the earth can also be interpreted intelligently. That is, that much more than simple ray tracing with a postulated reflection coefficient at some depth is possible. We show conclusively, using real subsurface probing data, that the target can be identified. It is emphasized that the identification is not simply a seismic-type map subject to interpretation and qualification by the observer but an actual processing scheme which inquires as to the presence of a particular target. We also stress that the methods developed in this dissertation are field-oriented and operate in real time. The paragraphs below itemize the specific progress which has been made.

The predictor-correlator method for characterizing and identifying subsurface targets was studied and extensively tested using real radar measurements obtained with a Terrascan-type subsurface pulse radar. Measurements were obtained over three sets of targets. The first set consisted of five similar-size targets including a plastic mine-like target, a brass cylinder, an aluminum sphere, a copper sheet and a wood board. These targets were buried at a depth of 5 cm (2 inches). The second set consisted of a series of different-size (maximum dimension varies from 30 cm to 300 cm) brass cylinders buried at different depths (depth varies from 30 cm to 150 cm). The third set consisted of a series of thin wires buried at the depth of 5 cm (2 inches). The method of characterization and identification uses the complex natural resonances as the discriminants for the identifier and the method of linear prediction for evaluation of the correlation coefficients for threshold identification. The complex natural resonances of the desired target are determined a priori and the difference equation coefficients related to these resonances are stored in the identification system for real-time on-location target identification. The identification process is simple and involves only simple algebraic operations.
The characterization and identification methods were found to be successful and a "first-generation" microcomputer system was built for on-location identification of mines in real time. A simple method for automatic tuning of the identification radar to the ground condition was suggested. This method is simple to use and can easily be incorporated into the microcomputer system for real-time target identification purposes. The significant findings are:

1. The identification method was extensively tested, with measurements over the subsurface targets, and found to be extremely successful. Single-look identification statistics for the identification of the mine-like target in different ground conditions were estimated to be $P_f=100\%, P_{FA}=2.25\%$ for $R_{ID}=30$ cm over an ensemble of 55 mine-like target waveforms and 222 other-target waveforms.* The $S/C$ of the ensemble of mine-like target waveforms ranged from 0.21 to 3.5.

2. A microcomputer system was implemented for real-time subsurface target identification using the techniques developed in this study. Single-look identification statistics for the identification of the mine-like target were estimated to be $P_f=100\%, P_{FA}=0\%$ for $R_{ID}=30$ cm over an ensemble of 30 mine-like target waveforms and 30 other-target waveforms. The amount of time required for a correct identification of the mine-like target was 10.5 seconds, a correct discrimination of an other-target or no-target required less time.

3. Identification performance degraded when the radar system was not tuned to the right ground condition.

4. Identification performance degraded when the radar frequencies did not properly span the target resonances.

5. Single-look identification performance was characterized by a correlation coefficient vs. sampling interval ($c(T)$) curve. Optimal identification performance occurred when the sampling interval $T$ was in the immediate neighborhood of $T_N$ (see Equation (51)). Thus, one knows a priori the value or the region of values of the sampling interval needed for design and implementation of the identification radar.

* Identification statistics given here is estimated from the ensemble of all mine-like target waveforms collected using the Terrascan-like systems.
6. All subsurface targets considered were characterized by a small and finite number (5 pairs or less) of resonances. These resonances were invariant with respect to radar location.

7. The resonances of the plastic mine-like target were found to be internal resonances, with their imaginary parts independent of ground condition. The resonances of the brass cylinder were found to be external resonances; both their imaginary and real parts were dependent on ground conditions.

8. The extracted resonances of the brass cylinders were found to be the dipoles modes along the length of the cylinder. Furthermore, they closely approximated the resonances of the same target buried in a homogeneous medium with plane-wave illumination. This discovery suggested a good way to estimate the ground parameters (see Section VII-B).

9. The high-frequency content of the backscattered waveforms was highly attenuated as target depth increased. Identification range decreased as target depth increased.

10. Up to a certain threshold, the frequency of the target resonances decreased according to the increase in target size, and target resonances depended solely on the scattering mechanisms of the targets. Beyond the threshold, increase in target size did not warrant the decrease in the frequency of the resonances. In this case, target resonances would depend on the scattering mechanisms as well as other quantities such as the antenna pattern, etc.

The significant contributions of this report are:

1. The problem of applying Prony's Method to real radar measurements for extraction of the complex resonances was considered as one of parameter optimization. This approach yielded legitimate target resonances from waveforms with S/C as low as 0.21 (see Chapter III).

2. The predictor-correlator method was extensively tested with real radar measurements, and found to yield practical single-look identification performance. Furthermore, it was found that there existed a limited range of T values in which optimum identification performance occurred. (See Chapter IV).
3. A microcomputer system was implemented for real-time on-location subsurface target identification using the techniques developed in this dissertation. The system was found to yield practical single-look identification performance with a 10.5 second identification time (see Chapter IX).

B. Conclusions

We have now provided a successful method for the identification of subsurface targets at shallow depth. The method is based on single radar returns and is simple to implement. Based on this method a microcomputer system has been implemented for on-location identification of subsurface targets in real time. Some modifications have to be made for the microcomputer identification radar system to be practical, the most important being a method to calibrate the ground parameters (ε, μ, σ) in real time and to adjust the resonances of the desired target accordingly for real-time subsurface target identification in different ground conditions. This is now being implemented and is expected to be incorporated in the final system.

C. Recommendations for Future Work

The subject of subsurface target characterization and identification is in its infancy. The results obtained in this study represents a significant step forward, but much remains to be done. The following items are highly recommended for future research:

1. The task of automatic on-location tuning of the subsurface radar to the ground condition is crucial to the problem of subsurface target identification. The consideration of the waveform values of the on-surface wire waveforms suggests a feasible way to solve this problem.

2. The relationships between the extracted resonances of the targets and the various system parameters such as target size, depth, antenna pattern, air-ground interface, etc., need to be exploited for a better understanding and interpretation of the extracted resonances.

3. Application of the characterization and identification technique to deeper targets needs to be expanded. In this regard very little deep electromagnetic probing has been done.

4. Identification of subsurface targets in the presence of other objects.
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This appendix derives Prony's method for the extraction of resonances from waveforms with multiple-order poles.

With multiple-order poles the transient waveform can be expressed as

$$r(t) = \sum_{i=1}^{N} \left[ \left( 1 + \sum_{j=2}^{M_i} b_{ji} p^{j-1} \right) a_i e^{s_i t} \right]$$  \hspace{1cm} (61)

where

$$p = 0, \text{ if } M_i < 2$$

$$p = 1, \text{ if } M_i \geq 2$$

and where $M_i$ is the multiplicity of the $i$th pole.

The corresponding expression of Equation (61) in the complex frequency domain is

$$\mathcal{Z}[r(t)] = \sum_{i=1}^{N} \left( \frac{a_i}{s - s_i} + \sum_{j=2}^{M_i} \frac{b_{ji} p^{j-1}}{(s - s_i)^j} \right)$$  \hspace{1cm} (62)

In discrete form, Equation (61) can be written as

$$r(nT) = \sum_{i=1}^{N} \left( 1 + \sum_{j=2}^{M_i} b_{ji} p^j (nT)^{j-1} \right) a_i e^{s_i nT}$$  \hspace{1cm} (63)

With the following $z$-transform pairs[54]

$$e^{s_i nT} = \frac{1}{1 - e^{-s_i T} z^{-1}}$$

150
\( z \left[ (nT)e^{s_1nT} \right] = \frac{T_0 e^{s_1 z^{-1}}}{(1-e^{s_1 z^{-1}})^2} \)

\( z \left[ (nT)^2e^{s_1nT} \right] = \frac{T^2 e^{s_1 z^{-1}} + s_1 T e^{s_1 z^{-1}}}{(1-e^{s_1 z^{-1}})^2} \)

\( z \left[ (nT)^j e^{s_1nT} \right] = \left( -Tz \frac{d}{dz} \right)^j \frac{1}{1-e^{s_1 z^{-1}}} \)

(64)

where \( z \left[ \right] \) is the z transform operation. We can transform Equation (63) into the z domain, viz.,

\[
\begin{align*}
\zeta \left[ r(nT) \right] &= \sum_{i=1}^{N} \left( 1 + \sum_{j=2}^{M_i} b_{ji} \left( -zT \frac{d}{dz} \right)^{j-1} \right) \frac{a_i}{s_1 z^{-1}} \\
&= \sum_{i=1}^{N} a_i \left( \frac{1}{s_1 z^{-1}} + \frac{b_{2i} T e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} \right) \\
&+ \frac{b_{3i} T^2 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \frac{b_{4i} T^3 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \cdots + b_{Mi} \left( Tz \frac{d}{dz} \right)^{M_i-1} \frac{1}{1-e^{s_1 z^{-1}}} \\
&= \sum_{i=1}^{N} a_i \left( \frac{1}{s_1 z^{-1}} + \frac{b_{2i} T e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} \right) \\
&+ \frac{b_{3i} T^2 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \frac{b_{4i} T^3 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \cdots + b_{Mi} \left( Tz \frac{d}{dz} \right)^{M_i-1} \frac{1}{1-e^{s_1 z^{-1}}} \\
&= \sum_{i=1}^{N} a_i \left( \frac{1}{s_1 z^{-1}} + \frac{b_{2i} T e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} \right) \\
&+ \frac{b_{3i} T^2 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \frac{b_{4i} T^3 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \cdots + b_{Mi} \left( Tz \frac{d}{dz} \right)^{M_i-1} \frac{1}{1-e^{s_1 z^{-1}}} \\
&= \sum_{i=1}^{N} a_i \left( \frac{1}{s_1 z^{-1}} + \frac{b_{2i} T e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} \right) \\
&+ \frac{b_{3i} T^2 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \frac{b_{4i} T^3 e^{s_1 z^{-1}}}{1-e^{s_1 z^{-1}}} + \cdots + b_{Mi} \left( Tz \frac{d}{dz} \right)^{M_i-1} \frac{1}{1-e^{s_1 z^{-1}}} \\
\zeta \left[ r(nT) \right] &= \frac{c_0 + c_1 z^{-1} + \cdots + c_{L-1} z^{-L+1}}{d_0 + d_1 z^{-1} + \cdots + d_L z^{-L}} \\
\zeta \left[ r(nT) \right] &= \frac{c_0 + c_1 z^{-1} + \cdots + c_{L-1} z^{-L+1}}{d_0 + d_1 z^{-1} + \cdots + d_L z^{-L}} \quad (65)
\end{align*}
\]

Each term in the right hand side of Equation (65) is a rational function of \( z^{-1} \) with its denominator one degree higher in \( z^{-1} \) than the numerator. Thus, when the series is summed, it becomes a rational function of \( z^{-1} \) in the form of

\[
\begin{align*}
\zeta \left[ r(nT) \right] &= \frac{c_0 + c_1 z^{-1} + \cdots + c_{L-1} z^{-L+1}}{d_0 + d_1 z^{-1} + \cdots + d_L z^{-L}} \\
\zeta \left[ r(nT) \right] &= \frac{c_0 + c_1 z^{-1} + \cdots + c_{L-1} z^{-L+1}}{d_0 + d_1 z^{-1} + \cdots + d_L z^{-L}} \quad (66)
\end{align*}
\]
where the polynomial of $z^{-1}$ in the denominator is one degree higher than that in the numerator. The denominator polynomial is commonly referred to as the characteristic polynomial and its related to the pole locations $s_i$ by

$$
\sum_{i=0}^{L} d_i z^{-i} = \prod_{i=1}^{N} \left(1 - e^{-z_i T} z^{-1}\right) M_i ; \quad L = \sum_{i=1}^{N} M_i
$$

(67)

Multiply both sides of Equation (67) by $z^L$, we obtain

$$
\sum_{i=0}^{L} d_i z^{L-i} = \prod_{i=1}^{N} \left(z - e^{-z_i T} z^{-1}\right) M_i \quad \text{or}
$$

$$
\sum_{m=0}^{L} 
\begin{bmatrix}
\vdots \\
\end{bmatrix} z^m = \prod_{i=1}^{N} \left(z - z_i\right) M_i
$$

(68)

where

$$
m = L-i; \quad m = 0,1 \cdots L
$$

$$
\tau_m = d_i
$$

$$
z_i = e^{-z_i T}
$$

(69)

Equation (68) is analogous to Equation (11).

We now proceed to write Equation (66) as

$$
d_0 + d_1 z^{-1} + \cdots + d_L z^{-L} \cdot [r(nT)] = c_0 + c_1 z^{-1} + \cdots + c_{L-1} z^{-L+1}
$$

(70)

With the relationship[54]

$$
\zeta^{-1} [z^{-\frac{1}{T}} (r(nT))] = r(nT-iT)
$$

(71)

where $\cdot^{-1} [ \cdot ]$ is the inverse z transform operation. We obtain the inverse z transform of Equation (70)

$$
\sum_{i=0}^{L} d_i r(nT-iT) = \zeta^{-1} \begin{bmatrix}
\vdots \\
\end{bmatrix} c_i z^{-i}
$$

(72)

Since the right-hand side of Equation (72) is zero for \( n > L \), hence

\[
\sum_{i=0}^{L} d_i r(nT-iT) = 0 \quad ; \quad n \geq L
\]

(73)

Now with

\[ n = L + K; \quad K = 0,1,2, \ldots \]
\[ m = L-i \quad \text{and} \]
\[ \eta_m = d_i \]

we obtain the desired difference equation,

\[
\sum_{m=0}^{L} \eta_m r(K+mT) = 0; \quad K = 0,1,2, \ldots
\]

(74)

where \( r_{K+m} = r(K+mT) \). This difference equation is identical to the Prony difference equation in Equation (12) except for the change of order. Thus, the sample values of a transient waveform with the presence of multiple-order poles satisfies a Prony difference equation of order \( L \), where

\[
L = \sum_{i=1}^{N} M_i
\]

(75)

With Equation (74) we can solve for the coefficients \( \eta_m \)'s, and subsequently solve for the \( s_i \) by Equation (67). We can also solve for the poles \( s_i \), as was done in the simple-pole case, by solving Equations (12) and (11) with \( N \) changed to \( L \). Thus, the same procedure taken to solve for the pole locations in the simple-pole case can also be used in the multiple-order-pole case. However, the procedure for the calculation of the residues requires a slight modification.

The calculation of the residues is done by solving Equation (63), which differs from Equation (8) because of the presence of the terms involving \( (nT) \), and the fact that there are \( L \) unknowns rather than \( N \). With the assumption that the \( i \)th pole is of order \( M_i \), Equation (63) can be written as
\[ r_0 = a_1 + a_2 + \cdots + a_N \]

\[ r_1 = a_1 z_1 + a_2 z_2 + \cdots + a_i z_i + T(b_2; a_1) z_1 + T(b_3; a_1) z_i + \cdots + T(b_{M_1}; a_i) z_i + \cdots + a_N z_N \]

\[ r_2 = a_1 z_1^2 + a_2 z_2^2 + \cdots + z_1 z_1 T(b_2; a_1) z_1^2 + z_1^2 z_2 + \cdots + z_1 z_1 T(b_3; a_1) z_1^2 + z_1^2 z_i + \cdots + z_1 z_1 T(b_{M_1}; a_i) z_i^2 + \cdots + a_N z_N^2 \]  

From Equation (75), we see that, in solving for the residues in the presence of multiple-order poles, the matrix Equation (15) must be modified as follows

\[ \text{DE} = F \]

where

\[ D = \begin{bmatrix} 1 & 1 & 1 & \cdots & 0 & 0 & \cdots & 1 & \cdots & 1 \\ z_1 & z_2 & z_3 & \cdots & z_1 & z_i & \cdots & z_1 & z_i+1 & \cdots & z_N \\ z_1^2 & z_2^2 & z_3^2 & \cdots & z_1^2 & z_i^2 & \cdots & z_1^2 & z_i+1 & \cdots & z_N^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ z_1^{L-1} & z_2^{L-1} & z_3^{L-1} & \cdots & z_1^{L-1} & z_i^{L-1} & \cdots & z_1^{L-1} & z_i+1 & \cdots & z_N^{L-1} \\ z_1^{L+1} & z_2^{L+1} & z_3^{L+1} & \cdots & z_1^{L+1} & z_i^{L+1} & \cdots & z_1^{L+1} & z_i+1 & \cdots & z_N^{L+1} \end{bmatrix} \]
\[ E = \begin{bmatrix} a_1 & \cdots & a_i & \cdots & a_{i+1} \\ a_2 & \cdots & a_i & \cdots & a_{i+1} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_i b_{2i} & \cdots & a_i b_{M_i} & \cdots & a_i b_{M_i} \\ a_i b_{3i} & \cdots & a_i b_{M_i+1} & \cdots & a_i b_{M_i+1} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_i b_{M_i} & \cdots & a_i b_{M_i+1} & \cdots & a_i b_{M_i+1} \\ a_{i+1} & \cdots & a_{i+1} & \cdots & a_{i+1} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_N & \cdots & a_N & \cdots & a_N \end{bmatrix} = \begin{bmatrix} a_1' & \cdots & a_i' & \cdots & a_{i+1}' \\ a_2' & \cdots & a_i' & \cdots & a_{i+1}' \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_i' b_{2i} & \cdots & a_i' b_{M_i} & \cdots & a_i' b_{M_i} \\ a_i' b_{3i} & \cdots & a_i' b_{M_i+1} & \cdots & a_i' b_{M_i+1} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_i' b_{M_i} & \cdots & a_i' b_{M_i+1} & \cdots & a_i' b_{M_i+1} \\ a_{i+1}' & \cdots & a_{i+1}' & \cdots & a_{i+1}' \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ a_N' & \cdots & a_N' & \cdots & a_N' \end{bmatrix} \]

\[ F = \begin{bmatrix} r_0 \\ r_1 \\ \vdots \\ r_{i-1} \\ r_i \\ r_{i+1} \\ \vdots \\ r_{i+M_i-2} \\ r_{i+M_i-1} \\ \vdots \\ r_{L-1} \end{bmatrix} \]
This appendix derives the variations of Prony's method due to the constraints \( a_1 = 1 \) (Interpolation method) and
\[
\sum_{m=0}^{N} a_m = 1
\]
(Eigenvalue method). Computer codes (in Fortran Language) for these methods are also included.

A. The Interpolation Method

In the interpolation method, the Prony difference equation can be written as
\[
\alpha_0 r(t) + \alpha_1 r(t+T) + \cdots + \alpha_{i-1} r(t+(i-1)T) + \cdots + \alpha_{i+1} r(t+(i+1)T) + \cdots
\]
\[
+ \alpha_N r(t+NT) = - \alpha_1 r(t+1)
\]
(76)

Thus the matrices A, B and C shown in Equation (13) need to be modified as
\[
AB = C
\]
(77)

where
\[
A = \begin{bmatrix}
r_0 & r_1 & \cdots & r_{i-1} & r_{i+1} & \cdots & r_N \\
r_1 & r_2 & \cdots & r_{i+1} & r_{i+2} & \cdots & r_{N+1} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
\vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
r_{M-N} & r_{M-N+1} & \cdots & r_{M-N+i-1} & r_{M-N+i+1} & \cdots & r_M
\end{bmatrix}
\]
Equation (77) can be used to solve for the coefficients $a_0, a_1, \ldots, a_{i-1}, a_{i+1}, \ldots, a_N$ in the interpolation method. Once the coefficients are known, we can solve for the poles and residues by following the identical procedure outlined in the Classical Method (Chapter III).

B. The Eigenvalue Method

Under the constraint

$$\sum_{m=0}^{N} a_m^2 = 1$$

the instantaneous error in the error-evaluation process of Prony is modified as follows

$$e(t+NT) = \sum_{m=0}^{N} a_m r_m(t+NT) \quad \sum_{m=0}^{N} a_m^2 = 1 \quad (78)$$

In matrix form, the instantaneous error can be written as
The total square error over the fitting interval \((t_s, t_s + MT - T)\) is

\[
L_1 = c_1 Tc_1
\]

\[
= B^T A^T A B
\]

\[
= B^T \phi B
\]

where \(L_1\) is the total squared error over the fitting interval. \([\cdot]\) denotes the transpose operation. \(\phi \equiv A^T A\), is the data covariance matrix [53].

Solving for Matrix B by minimizing \(L_1\) under the constraint

\[
\sum_{m=0}^{N} a_m^2 = 1
\]

is a standard eigenvalue problem. Via the eigen-analysis, the solution matrix \(B\) is the eigen-vector corresponding to the minimum eigenvalue of the covariance matrix \(\phi\).

Thus, Equation (80) can be used to solve for the coefficients \(a_0, a_1, \ldots, a_N\). Once these coefficients are known the identical procedure outlined in the Classical Prony's method can be used to solve for the poles and residues.

Computer codes for the Prony's method and its variations are given below. The program names "SEMI" implements the Prony's method under the constraints of \(a_m = 1, m = 0, 1, 2 \cdots N\) (See Chapter III). The program "Sem2" implements the Prony's method under the constraint of

\[
\sum_{m=0}^{N} a_m^2 = 1
\]

Both programs are well commented and user oriented.
231  CCC
232  CCC  7)  SOLVE  FOR  THE  ALPHAN
233  CLC  ***********************
234  CCC
235  X = [I + (1/4) + (1/4)]
236  V = [I + (1/4) + (1/4)]
237  W = [I + (1/4) + (1/4)]
238  Y = [I + (1/4) + (1/4)]
239  Z = [I + (1/4) + (1/4)]
240  CCC
241  CCC  =  SOLVE  FOR  I:  51 = (1/4) + (1/4) = (1)
242  CCC  ***********************
FC
19 FC 11 SHOW OUT A FOR THE PROGRAM START
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310 C
**FUNCTION NAME**: AREA (SIMPLIFIED EXPANSION BY FOCUS)

**FUNCTIONAL DESCRIPTION**: This function extracts the six points from the ellipse.

**PARAMETERS**: (IN)
- **RADIUS**: The radius of the ellipse.
- **FOCUS**: The focus of the ellipse.

**RETURN VALUE**: The six points extracted from the ellipse.

**IMPLEMENTATION METHOD**:
- **Algorithm**: Iterative method.
- **Implementation**: Uses a pre-defined algorithm to extract the points.

**ERROR HANDLING**: None specified.

**AUTHOR**: Unknown

**DATE**: Unknown

**SOURCE**: Unknown
...
APPENDIX C

This appendix tabulates the extracted resonances of the mine-like target at different antenna locations in icy ground. The poles, residues as well as the minimum-error-case parameters associated with the Prony Process are given. These parameters are N, IBS, III, and M and are defined as follows.

N = Number of poles

IBS = Interval between samples, i.e., T = IBSxTB

III = The start time of the fitting interval in the Prony process is t_s + (III - 1)x2xTB

M = Number of samples used in the fitting interval is MxN.
TABLE 17
EXTRACTED RESONANCES OF THE MINE-LIKE TARGET
AT VARIOUS ANTENNA LOCATIONS IN ICY GROUND

<table>
<thead>
<tr>
<th>ANTENNA LOCATION = CENTER</th>
<th>N=11, IBS=5, III=5, M=3</th>
<th>( r=0.632\times10^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
</tr>
<tr>
<td>( -0.6165323\times10^{8} \pm 0.5980379\times10^{8} ) ( -0.1627237\times10^{0} \pm 0.2243193\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.9816088\times10^{8} \pm 0.1153422\times10^{8} ) ( -0.1200819\times10^{0} \pm 0.4662508\times10^{-1} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.2972145\times10^{8} \pm 0.3199646\times10^{8} ) ( -0.6727021\times10^{0} \pm 0.2928001\times10^{-1} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.2574395\times10^{8} \pm 0.4525337\times10^{8} ) ( -0.2245250\times10^{0} \pm 0.9734140\times10^{-1} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15 cm EAST OF CENTER</th>
<th>N=11, IBS=7, III=1, M=2</th>
<th>( r=0.604\times10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
</tr>
<tr>
<td>( -0.7955566\times10^{9} \pm 0.7207162\times10^{8} ) ( -0.3441590\times10^{0} \pm 0.5773295\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.9747022\times10^{8} \pm 0.1327517\times10^{8} ) ( -0.2914887\times10^{-1} \pm 0.4185661\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.2185998\times10^{9} \pm 0.1964866\times10^{8} ) ( -0.1786104\times10^{1} \pm 0.6787741\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.2235675\times10^{8} \pm 0.2570622\times10^{8} ) ( -0.1210215\times10^{1} \pm 0.1495749\times10^{1} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.2108089\times10^{8} \pm 0.3265433\times10^{8} ) ( -0.2914887\times10^{-1} \pm 0.4185661\times10^{0} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15 cm SOUTH OF CENTER</th>
<th>N=10, IBS=4, III=2, M=2</th>
<th>( r=0.375\times10^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
<td>POL_POL_RESIDUE _RESIDUE</td>
</tr>
<tr>
<td>( -0.4419169\times10^{8} \pm 0.5302244\times10^{8} ) ( -0.1283107\times10^{0} \pm 0.2668165\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.1687482\times10^{9} \pm 0.1862940\times10^{9} ) ( -0.1938946\times10^{0} \pm 0.4774533\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.1862333\times10^{9} \pm 0.2797166\times10^{9} ) ( -0.2234024\times10^{-1} \pm 0.5512929\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.3106326\times10^{8} \pm 0.3993629\times10^{8} ) ( -0.5570095\times10^{-1} \pm 0.4816286\times10^{0} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( -0.4141821\times10^{8} \pm 0.5571886\times10^{8} ) ( -0.7225376\times10^{0} \pm 0.9451689\times10^{0} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Real and imaginary parts of the extracted resonances are in Nepers/s and Hz, respectively.*
### TABLE 17 (Cont.)

<table>
<thead>
<tr>
<th>15 cm WEST OF CENTER</th>
<th>N=7, IBS=9, III=3, M=3</th>
<th>c=0.448E-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POLE</strong> (REAL PART)</td>
<td><strong>POLE</strong> (IMAG PART)</td>
<td><strong>RESIDUE</strong> (REAL PART)</td>
</tr>
<tr>
<td>-.8252691E8</td>
<td>±.7159227E8</td>
<td>.4703710E0</td>
</tr>
<tr>
<td>-.6366100E8</td>
<td>±.1213223E9</td>
<td>.2435532E-1</td>
</tr>
<tr>
<td>-.2474290E9</td>
<td>±.2123833E9</td>
<td>.3750488E0</td>
</tr>
<tr>
<td>-.1196715E9</td>
<td>±.2833333E9</td>
<td>.1486354E9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15 cm NORTH OF CENTER</th>
<th>N=12, IBS=6, III=5, M=2</th>
<th>c=0.287E-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POLE</strong> (REAL PART)</td>
<td><strong>POLE</strong> (IMAG PART)</td>
<td><strong>RESIDUE</strong> (REAL PART)</td>
</tr>
<tr>
<td>-.1238699E9</td>
<td>±.5956967E8</td>
<td>-.7568201E0</td>
</tr>
<tr>
<td>-.1455328E9</td>
<td>±.1044725E9</td>
<td>.4427186E0</td>
</tr>
<tr>
<td>-.2976452E9</td>
<td>±.2543575E9</td>
<td>.1651730E0</td>
</tr>
<tr>
<td>-.3582517E9</td>
<td>±.3319750E9</td>
<td>.3949756E0</td>
</tr>
<tr>
<td>-.3250828E9</td>
<td>±.4250000E9</td>
<td>.2408422E0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>30 cm EAST OF CENTER</th>
<th>N=11, IBS=6, III=4, M=2</th>
<th>c=0.247E-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POLE</strong> (REAL PART)</td>
<td><strong>POLE</strong> (IMAG PART)</td>
<td><strong>RESIDUE</strong> (REAL PART)</td>
</tr>
<tr>
<td>-.9395546E8</td>
<td>±.7131887E8</td>
<td>-.3951318E0</td>
</tr>
<tr>
<td>-.1369431E9</td>
<td>±.1220007E9</td>
<td>-.1243418E1</td>
</tr>
<tr>
<td>-.3187709E9</td>
<td>±.2553446E9</td>
<td>-.1835029E0</td>
</tr>
<tr>
<td>-.2052859E9</td>
<td>±.3777737E9</td>
<td>.1061165E0</td>
</tr>
<tr>
<td>-.2686828E9</td>
<td>±.4250000E9</td>
<td>-.2203826E0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>30 cm SOUTH OF CENTER</th>
<th>N=13, IBS=6, III=2, M=2</th>
<th>c=0.406E-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POLE</strong> (REAL PART)</td>
<td><strong>POLE</strong> (IMAG PART)</td>
<td><strong>RESIDUE</strong> (REAL PART)</td>
</tr>
<tr>
<td>-.7440484E8</td>
<td>±.5768431E8</td>
<td>.2634359E0</td>
</tr>
<tr>
<td>-.2734229E9</td>
<td>±.1749879E9</td>
<td>.5841965E0</td>
</tr>
<tr>
<td>-.2451866E9</td>
<td>±.2365293E9</td>
<td>.1394630E1</td>
</tr>
<tr>
<td>-.2480318E9</td>
<td>±.2889975E9</td>
<td>.6811801E0</td>
</tr>
<tr>
<td>-.7653034E9</td>
<td>±.3814169E9</td>
<td>-.6790937E0</td>
</tr>
</tbody>
</table>
### TABLE 17 (Cont.)

<table>
<thead>
<tr>
<th>30 cm WEST OF CENTER</th>
<th>N=13, IBS=6, III=3, M=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLE (REAL PART)</td>
<td>POLE (IMAG PART)</td>
</tr>
<tr>
<td>-1.174326E9</td>
<td>±.9037581E8</td>
</tr>
<tr>
<td>-2.722184E9</td>
<td>±.1783297E9</td>
</tr>
<tr>
<td>-2.442735E9</td>
<td>±.3781778E9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>30 cm NORTH OF CENTER</th>
<th>N=12, IBS=6, III=2, M=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>POLE (REAL PART)</td>
<td>POLE (IMAG PART)</td>
</tr>
<tr>
<td>-3.929171E8</td>
<td>±.6274667E8</td>
</tr>
<tr>
<td>-3.953903E8</td>
<td>±.1162181E9</td>
</tr>
<tr>
<td>-2.863506E9</td>
<td>±.1847860E9</td>
</tr>
<tr>
<td>-2.130829E9</td>
<td>±.2626060E9</td>
</tr>
<tr>
<td>-3.845860E9</td>
<td>±.2977974E9</td>
</tr>
<tr>
<td>-3.482679E9</td>
<td>±.3921698E9</td>
</tr>
</tbody>
</table>

**AVERAGE**

<table>
<thead>
<tr>
<th>POLE (REAL PART)</th>
<th>POLE (IMAG PART)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7.493116E8</td>
<td>±.6347621E8</td>
</tr>
<tr>
<td>-9.981995E8</td>
<td>±.1146406E9</td>
</tr>
<tr>
<td>-2.416503E9</td>
<td>±.535799E9</td>
</tr>
<tr>
<td>-2.609195E9</td>
<td>±.3074991E9</td>
</tr>
<tr>
<td>-2.685226E9</td>
<td>±.4076659E9</td>
</tr>
</tbody>
</table>
This appendix tabulates the average extracted resonances of mine-like target waveforms obtained using the 12m long antenna.

Table 18
AVERAGE EXTRACTED RESONANCES OF THE MINE-LIKE TARGET WAVEFORMS OBTAINED USING THE 12m LONG ANTENNA

<table>
<thead>
<tr>
<th>POLE (REAL)*</th>
<th>POLE (IMAG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-242.9760E6</td>
<td>144.343E6</td>
</tr>
<tr>
<td>-381.1344E6</td>
<td>233.9871E6</td>
</tr>
<tr>
<td>-407.1770E6</td>
<td>319.0055E6</td>
</tr>
<tr>
<td>-373.7482E6</td>
<td>413.1869E6</td>
</tr>
</tbody>
</table>

*Real and imaginary parts of the extracted resonances are in Nepers/s and Hz, respectively.
APPENDIX E

This appendix lists the Fortran program for performing the target identification process (SRTID2), it also tabulates some of the target identification results described in Chapter IV. Detail correlation coefficient values are given.
I

**PHASE LAGS**

**IDENTIFICATION**

**PHASE LAGS**

**IDENTIFICATION**
193

111 FCF
112 FCF
113 FCF  \* NOT ADDITIONAL VERTICAL OFFSET
114 FCF
115 FCF
116 FCF
117 CALL UF104(15)
118 x=x=1.41
119 \*x=1.41
120 u 11 \*x=1.7
121 11 y=x+y+u1(u+1)/2
122 v u 12 \*x=1.26
123 12 \*x=x+y+u1u1=1.7
124 \*x=x+y+u1
125 v u=x
126 v u=2.5
127 v u=1.5
128 v u=3.3
129 \*x=9+1(u)
130 11110 y3=I1F1(1x+1)
131 \*x=x+y+u1+u2(LT+AS)(31) uCTn = 21
132 \*x=x+y+u1+u2(LT+AS)(31) uCTn = 2119
133 21 v T1 = 1
134 212 v u=x-y1
135 22 v u=7.56
136 22 v (u)=1.41
137 23 v u=7.56
138 23 v u=7.56
139 23 v u=7.56
140 23 v u=7.56
141 23 v u=7.56
142 \*x=x+y+u1
143 \*x=x+y+u1
144 \*x=x+y+u1
145 \*x=x+y+u1
146 \*x=x+y+u1
147 \*x=x+y+u1
148 \*x=x+y+u1
149 \*x=x+y+u1
150 \*x=x+y+u1
151 \*x=x+y+u1
152 \*x=x+y+u1
153 \*x=x+y+u1
154 \*x=x+y+u1
155 \*x=x+y+u1
156 \*x=x+y+u1
157 \*x=x+y+u1
158 \*x=x+y+u1
159 \*x=x+y+u1
160 \*x=x+y+u1
199

147 1'9' 4e47

112 1'9' 4e47

138 1'9' 4e47

102 1'9' 4e47

120 1'9' 4e47

146 1'9' 4e47

114 1'9' 4e47

88 1'9' 4e47

60 1'9' 4e47

38 1'9' 4e47

16 1'9' 4e47

6 1'9' 4e47

4 1'9' 4e47

2 1'9' 4e47
<table>
<thead>
<tr>
<th>WAVEFORM</th>
<th>ANTENNA LOCATION</th>
<th>$r(9T_B)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E, S</td>
<td></td>
<td>.593</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>.167</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td>.785</td>
</tr>
<tr>
<td>C</td>
<td>15 cm, E</td>
<td>.170</td>
</tr>
<tr>
<td>C</td>
<td>15 cm, S</td>
<td>.596</td>
</tr>
<tr>
<td>C</td>
<td>15 cm, W</td>
<td>.382</td>
</tr>
<tr>
<td>C</td>
<td>15 cm, N</td>
<td>.296</td>
</tr>
<tr>
<td>C</td>
<td>30 cm, E</td>
<td>.183</td>
</tr>
<tr>
<td>C</td>
<td>30 cm, S</td>
<td>.294</td>
</tr>
<tr>
<td>C</td>
<td>30 cm, W</td>
<td>.766</td>
</tr>
<tr>
<td>C</td>
<td>30 cm, N</td>
<td>.288</td>
</tr>
<tr>
<td>C</td>
<td>45 cm, E</td>
<td>-.478</td>
</tr>
<tr>
<td>C</td>
<td>45 cm, S</td>
<td>.678</td>
</tr>
<tr>
<td>BRASS</td>
<td>C</td>
<td>-.678</td>
</tr>
<tr>
<td>CYLINDER</td>
<td>15 cm, S</td>
<td>-.380</td>
</tr>
<tr>
<td></td>
<td>30 cm, S</td>
<td>-.448</td>
</tr>
<tr>
<td></td>
<td>45 cm, W</td>
<td>-.447</td>
</tr>
<tr>
<td>ALUMINUM SPHERE</td>
<td>7 cm, S</td>
<td>-.337</td>
</tr>
<tr>
<td></td>
<td>22 cm, S</td>
<td>-.387</td>
</tr>
<tr>
<td></td>
<td>37 cm, S</td>
<td>-.061</td>
</tr>
<tr>
<td>COPPER SHEET</td>
<td>7 cm, N</td>
<td>-.727</td>
</tr>
<tr>
<td></td>
<td>10 cm, S</td>
<td>-.384</td>
</tr>
<tr>
<td></td>
<td>25 cm, S</td>
<td>-.026</td>
</tr>
<tr>
<td></td>
<td>13 cm, NE</td>
<td>-.065</td>
</tr>
<tr>
<td></td>
<td>28 cm, NE</td>
<td>-.183</td>
</tr>
</tbody>
</table>
TABLE 20
VALUES OF THE CORRELATION COEFFICIENT FOR THE IDENTIFICATION OF THE MINE-LIKE TARGET IN DRY GROUND

<table>
<thead>
<tr>
<th>WAVEFORM</th>
<th>ANTENNA LOCATION</th>
<th>$\cap(9T_B)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINE-LIKE TARGET</td>
<td>C</td>
<td>.575</td>
</tr>
<tr>
<td></td>
<td>15 cm,E</td>
<td>.685</td>
</tr>
<tr>
<td></td>
<td>15 cm,S</td>
<td>.709</td>
</tr>
<tr>
<td></td>
<td>15 cm,W</td>
<td>.483</td>
</tr>
<tr>
<td></td>
<td>15 cm,N</td>
<td>.538</td>
</tr>
<tr>
<td>BRASS CYLINDER</td>
<td>C</td>
<td>-.779</td>
</tr>
<tr>
<td>ALUMINUM SPHERE</td>
<td>7 cm,S</td>
<td>-.080</td>
</tr>
<tr>
<td>COPPER SHEET</td>
<td>10 cm,S</td>
<td>-.291</td>
</tr>
</tbody>
</table>
### Table 21
VALUES OF THE CORRELATION COEFFICIENTS FOR THE IDENTIFICATION OF THE MINE-LIKE TARGET AND THE BRASS CYLINDER IN DRY GROUND

<table>
<thead>
<tr>
<th>WAVEFORM</th>
<th>ANTENNA LOCATION</th>
<th>DESIRED TARGET = MINE-LIKE TARGET $\rho(\theta_{TB})$</th>
<th>DESIRED TARGET = BRASS CYLINDER $\rho(\gamma_{TB})$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MINE-LIKE TARGET</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>.525</td>
<td>.648</td>
</tr>
<tr>
<td></td>
<td>15 cm, E</td>
<td>.434</td>
<td>.646</td>
</tr>
<tr>
<td></td>
<td>15 cm, S</td>
<td>.423</td>
<td>.491</td>
</tr>
<tr>
<td></td>
<td>15 cm, W</td>
<td>.477</td>
<td>.651</td>
</tr>
<tr>
<td></td>
<td>15 cm, N</td>
<td>.837</td>
<td>.922</td>
</tr>
<tr>
<td></td>
<td>30 cm, E</td>
<td>.687</td>
<td>.738</td>
</tr>
<tr>
<td></td>
<td>30 cm, S</td>
<td>.535</td>
<td>.168</td>
</tr>
<tr>
<td></td>
<td>30 cm, W</td>
<td>.396</td>
<td>.831</td>
</tr>
<tr>
<td></td>
<td>30 cm, N</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>BRASS CYLINDER</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>-.266</td>
<td>.954</td>
</tr>
<tr>
<td></td>
<td>15 cm, SN</td>
<td>.228</td>
<td>.983</td>
</tr>
<tr>
<td></td>
<td>30 cm, SN</td>
<td>.146</td>
<td>.951</td>
</tr>
<tr>
<td></td>
<td>15 cm, EW</td>
<td>.228</td>
<td>.979</td>
</tr>
<tr>
<td></td>
<td>30 cm, EW</td>
<td>-.049</td>
<td>.991</td>
</tr>
</tbody>
</table>
TABLE 22
DETERMINING THE DETECTION AND IDENTIFICATION THRESHOLDS FOR THE
IDENTIFICATION OF THE Mine-LIKE TARGET. R_{ID} = 30 cm

<table>
<thead>
<tr>
<th>ANTENNA</th>
<th>C</th>
<th>15 cm(_S)</th>
<th>30 cm(_S)</th>
<th>15 cm(_N)</th>
<th>30 cm(_N)</th>
<th>15 cm(_E)</th>
<th>30 cm(_E)</th>
<th>15 cm(_N)</th>
<th>30 cm(_N)</th>
<th>MINIMUM +T_{01} = \Theta_{THI}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu(59_g))</td>
<td>0.445</td>
<td>0.969</td>
<td>0.984</td>
<td>0.527</td>
<td>0.921</td>
<td>0.890</td>
<td>0.812</td>
<td>0.894</td>
<td>0.939</td>
<td>0.445</td>
</tr>
<tr>
<td>(\nu(6T_B))</td>
<td>-0.0213</td>
<td>0.800</td>
<td>0.795</td>
<td>0.184</td>
<td>0.394</td>
<td>-0.365</td>
<td>-0.488</td>
<td>-0.379</td>
<td>-0.036</td>
<td>-0.488</td>
</tr>
<tr>
<td>(\nu(7T_B))</td>
<td>0.536</td>
<td>0.875</td>
<td>0.827</td>
<td>0.487</td>
<td>0.707</td>
<td>0.373</td>
<td>0.253</td>
<td>0.127</td>
<td>0.206</td>
<td>0.127</td>
</tr>
<tr>
<td>(\nu(8T_B))</td>
<td>0.561</td>
<td>0.936</td>
<td>0.813</td>
<td>0.433</td>
<td>0.687</td>
<td>0.453</td>
<td>0.450</td>
<td>0.322</td>
<td>0.243</td>
<td>0.243</td>
</tr>
<tr>
<td>(\nu(9T_B))</td>
<td>0.658</td>
<td>0.902</td>
<td>0.705</td>
<td>0.293</td>
<td>0.396</td>
<td>0.321</td>
<td>0.679</td>
<td>0.533</td>
<td>0.289</td>
<td>0.289</td>
</tr>
<tr>
<td>(\nu(10T_B))</td>
<td>0.822</td>
<td>0.952</td>
<td>0.727</td>
<td>0.221</td>
<td>0.426</td>
<td>0.464</td>
<td>0.749</td>
<td>0.593</td>
<td>0.542</td>
<td>0.221</td>
</tr>
<tr>
<td>(\nu(11T_B))</td>
<td>0.922</td>
<td>0.902</td>
<td>0.821</td>
<td>0.436</td>
<td>0.522</td>
<td>0.545</td>
<td>0.832</td>
<td>0.517</td>
<td>0.504</td>
<td>0.436</td>
</tr>
<tr>
<td>(\nu(12T_B))</td>
<td>0.0424</td>
<td>-0.194</td>
<td>-0.243</td>
<td>-0.177</td>
<td>-0.259</td>
<td>-0.0213</td>
<td>0.236</td>
<td>0.177</td>
<td>0.240</td>
<td>-0.259</td>
</tr>
<tr>
<td>(\nu(5T_B-12T_B))</td>
<td>0.4954</td>
<td>0.76761</td>
<td>0.67871</td>
<td>0.30050</td>
<td>0.47297</td>
<td>0.33235</td>
<td>0.44311</td>
<td>0.34789</td>
<td>0.33204</td>
<td>0.30050</td>
</tr>
</tbody>
</table>

| F_{MAX} | 38     | 41         | 68          | 39          | 28          | 28          | 69          | 40          | 27          | RANGE=27,69   |
| F_{MAX}** | 2.82380| 2.53884    | 1.84263     | 2.14075     | 1.73829     | 3.14312     | 1.66354     | 2.57983     | 2.18490     | RANGE=1.66354,2.82380 |
| F_{MAX}*** | 0.20548| 2.6127     | 3.2341      | 2.5412      | 2.21247     | 0.69875     | 1.6681      | 3.0058      | 0.59804     | RANGE=1.6681,3.4058 |

\*F_{MAX} is in units of T_{B}

\**F_{MAX} is in units of 200 mv

\***F_{MAX} is in units of (200 mv)^c
# Table 23

<table>
<thead>
<tr>
<th>Location</th>
<th>C 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>E 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>MIN/MAX g₁₁₁₁ = Ph₁₁₁₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 cm</td>
<td>0.975</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>570 cm</td>
<td>0.954</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>620 cm</td>
<td>0.947</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>650 cm</td>
<td>0.916</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>740 cm</td>
<td>0.884</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>780 cm</td>
<td>0.856</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>840 cm</td>
<td>0.811</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>970 cm</td>
<td>0.779</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>1040 cm</td>
<td>0.752</td>
<td>0.930</td>
<td>0.900</td>
</tr>
</tbody>
</table>

Notes:
- **N** is in units of 200 µW/cm²
- **B** is in units of 200 µW/cm²
- **H** is in units of 200 µW/cm²

---

**Table 23 continued...**

<table>
<thead>
<tr>
<th>Location</th>
<th>C 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>E 15 cm S 30 cm S 15 cm N 30 cm N</th>
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<tr>
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<td>0.947</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
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<td>0.916</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
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<td>0.930</td>
<td>0.900</td>
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<tr>
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<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
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<td>0.811</td>
<td>0.930</td>
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<td>0.779</td>
<td>0.930</td>
<td>0.900</td>
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<td>0.752</td>
<td>0.930</td>
<td>0.900</td>
</tr>
</tbody>
</table>

---

**Table 23 continued...**

<table>
<thead>
<tr>
<th>Location</th>
<th>C 15 cm S 30 cm S 15 cm N 30 cm N</th>
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<tr>
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<td>0.947</td>
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<td>0.900</td>
</tr>
<tr>
<td>650 cm</td>
<td>0.916</td>
<td>0.930</td>
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<td>0.884</td>
<td>0.930</td>
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</tr>
<tr>
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<td>0.856</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>840 cm</td>
<td>0.811</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
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<td>0.779</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>1040 cm</td>
<td>0.752</td>
<td>0.930</td>
<td>0.900</td>
</tr>
</tbody>
</table>

**Table 23 continued...**

<table>
<thead>
<tr>
<th>Location</th>
<th>C 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>E 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>MIN/MAX g₁₁₁₁ = Ph₁₁₁₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 cm</td>
<td>0.975</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>570 cm</td>
<td>0.954</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>620 cm</td>
<td>0.947</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>650 cm</td>
<td>0.916</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>740 cm</td>
<td>0.884</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>780 cm</td>
<td>0.856</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>840 cm</td>
<td>0.811</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>970 cm</td>
<td>0.779</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>1040 cm</td>
<td>0.752</td>
<td>0.930</td>
<td>0.900</td>
</tr>
</tbody>
</table>

---

**Table 23 continued...**

<table>
<thead>
<tr>
<th>Location</th>
<th>C 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>E 15 cm S 30 cm S 15 cm N 30 cm N</th>
<th>MIN/MAX g₁₁₁₁ = Ph₁₁₁₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 cm</td>
<td>0.975</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>570 cm</td>
<td>0.954</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>620 cm</td>
<td>0.947</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>650 cm</td>
<td>0.916</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>740 cm</td>
<td>0.884</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>780 cm</td>
<td>0.856</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>840 cm</td>
<td>0.811</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>970 cm</td>
<td>0.779</td>
<td>0.930</td>
<td>0.900</td>
</tr>
<tr>
<td>1040 cm</td>
<td>0.752</td>
<td>0.930</td>
<td>0.900</td>
</tr>
</tbody>
</table>
### Table 24
DETERMINING THE DETECTION AND IDENTIFICATION THRESHOLDS FOR THE IDENTIFICATION OF THE ALUMINUM SPHERE. $R_{ID} = 37$ cm

<table>
<thead>
<tr>
<th>Antenna Location</th>
<th>E,S</th>
<th>15 cm,S</th>
<th>30 cm,S</th>
<th>E,N</th>
<th>15 cm,N</th>
<th>30 cm,N</th>
<th>E,E</th>
<th>15 cm,E</th>
<th>30 cm,E</th>
<th>E,W</th>
<th>15 cm,W</th>
<th>30 cm,W</th>
<th>MINIMUM $i_{TD1} = i_{TH1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(5T_B)$</td>
<td>.523</td>
<td>.691</td>
<td>.825</td>
<td>.137</td>
<td>.603</td>
<td>.762</td>
<td>.764</td>
<td>.732</td>
<td>.812</td>
<td>.401</td>
<td>.924</td>
<td>.708</td>
<td>.197</td>
</tr>
<tr>
<td>$(6T_B)$</td>
<td>.481</td>
<td>.746</td>
<td>.746</td>
<td>.631</td>
<td>.727</td>
<td>.786</td>
<td>.678</td>
<td>.783</td>
<td>.735</td>
<td>.745</td>
<td>.922</td>
<td>.803</td>
<td>.481</td>
</tr>
<tr>
<td>$(7T_B)$</td>
<td>.751</td>
<td>.862</td>
<td>.840</td>
<td>.600</td>
<td>.943</td>
<td>.752</td>
<td>.772</td>
<td>.832</td>
<td>.666</td>
<td>.790</td>
<td>.879</td>
<td>.765</td>
<td>.600</td>
</tr>
<tr>
<td>$(8T_B)$</td>
<td>.708</td>
<td>.837</td>
<td>.813</td>
<td>.123</td>
<td>.936</td>
<td>.589</td>
<td>.623</td>
<td>.743</td>
<td>.106</td>
<td>.361</td>
<td>.661</td>
<td>.571</td>
<td>-.106</td>
</tr>
<tr>
<td>$(9T_B)$</td>
<td>.621</td>
<td>.852</td>
<td>.825</td>
<td>.345</td>
<td>.870</td>
<td>.603</td>
<td>.277</td>
<td>.312</td>
<td>.637</td>
<td>.250</td>
<td>.218</td>
<td>.219</td>
<td>.218</td>
</tr>
<tr>
<td>$(10T_B)$</td>
<td>.810</td>
<td>.896</td>
<td>.926</td>
<td>.444</td>
<td>.629</td>
<td>.823</td>
<td>.730</td>
<td>.830</td>
<td>.666</td>
<td>.189</td>
<td>.709</td>
<td>.792</td>
<td>.189</td>
</tr>
<tr>
<td>$(11T_B)$</td>
<td>.590</td>
<td>.723</td>
<td>.945</td>
<td>.541</td>
<td>.103</td>
<td>.794</td>
<td>.826</td>
<td>.828</td>
<td>.648</td>
<td>.395</td>
<td>.722</td>
<td>.795</td>
<td>.103</td>
</tr>
<tr>
<td>$(12T_B)$</td>
<td>.596</td>
<td>.617</td>
<td>.818</td>
<td>.365</td>
<td>.0464</td>
<td>.802</td>
<td>.837</td>
<td>.376</td>
<td>.624</td>
<td>.341</td>
<td>.584</td>
<td>.650</td>
<td>.341</td>
</tr>
<tr>
<td>$(5T_B=12T_B)$</td>
<td>.66711</td>
<td>.77723</td>
<td>.85132</td>
<td>.44250</td>
<td>.64322</td>
<td>.76397</td>
<td>.71905</td>
<td>.66172</td>
<td>.62796</td>
<td>.42942</td>
<td>.73454</td>
<td>.66865</td>
<td>.42942</td>
</tr>
</tbody>
</table>

\[ t_{MAX} \] **

\[ t_{MIN} \] ***

\[ t_{MAX} \] ****

\[ t_{MIN} \] *****

* Antenna Location here is referenced to edge of sphere
** $t_{MAX}$ is units of $T_B$
*** $MAX$ is units of 200 mV
**** $t_{MIN}$ is units of (200 mV)
APPENDIX F

This appendix tabulates the average extracted resonances of the different-size, different-depth cylinders and the thin wires (discussed in Chapter V).
<table>
<thead>
<tr>
<th>DEPTH</th>
<th>30 cm</th>
<th>90 cm</th>
<th>150 cm</th>
<th>300 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>POLE (REAL)</td>
<td>POLE (IMAG)</td>
<td>POLE (REAL)</td>
<td>POLE (IMAG)</td>
</tr>
<tr>
<td>30 cm</td>
<td>-169.5810911E6</td>
<td>60.75085522E6</td>
<td>-194.1313250E6</td>
<td>-197.0824271E6</td>
</tr>
<tr>
<td></td>
<td>-195.4750776E6</td>
<td>111.32925110E6</td>
<td>-207.6996313E6</td>
<td>-143.9250667E6</td>
</tr>
<tr>
<td>90 cm</td>
<td>-160.8150820E6</td>
<td>211.9305600E6</td>
<td>-193.9141500E6</td>
<td>-260.8286500E6</td>
</tr>
<tr>
<td></td>
<td>-31.6147124E6</td>
<td>306.1199511E6</td>
<td>-226.3574500E6</td>
<td>-229.9907842E6</td>
</tr>
<tr>
<td>150 cm</td>
<td>-140.6709682E6</td>
<td>451.3666125E6</td>
<td>-343.8292000E6</td>
<td>-409.2697000E6</td>
</tr>
<tr>
<td></td>
<td>-296.3700176E6</td>
<td>66.8628111E6</td>
<td>-184.7466796E6</td>
<td>-144.4790996E6</td>
</tr>
<tr>
<td></td>
<td>-192.9532500E6</td>
<td>112.3268500E6</td>
<td>-210.5452500E6</td>
<td>-163.5855200E6</td>
</tr>
<tr>
<td>300 cm</td>
<td>-140.7522536E6</td>
<td>205.9555900E6</td>
<td>-167.9089964E6</td>
<td>-347.7611500E6</td>
</tr>
<tr>
<td></td>
<td>-157.2403618E6</td>
<td>302.7963550E6</td>
<td>-99.9776536E6</td>
<td>-351.1995500E6</td>
</tr>
</tbody>
</table>

* Real Part in Nepers/s, Imaginary Part in Hz.
### TABLE 26
AVERAGE EXTRACTED RESONANCES OF THE 5cm DEEP DIFFERENT-LENGTH THIN WIRES

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>30 cm</th>
<th>45 cm</th>
<th>60 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole (real)</td>
<td>Pole (imag)</td>
<td>Pole (real)</td>
<td>Pole (imag)</td>
</tr>
<tr>
<td>5 cm</td>
<td>-239.266800E6</td>
<td>70.722780E6</td>
<td>-154.095000E6</td>
</tr>
<tr>
<td></td>
<td>-134.151920E6</td>
<td>110.254300E6</td>
<td>-98.180172E6</td>
</tr>
<tr>
<td></td>
<td>-144.240780E6</td>
<td>124.259320E6</td>
<td>-148.281033E6</td>
</tr>
<tr>
<td></td>
<td>-143.758252E6</td>
<td>304.801540E6</td>
<td>-163.734933E6</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>45 cm</td>
<td>60 cm</td>
</tr>
<tr>
<td>Pole (real)</td>
<td>Pole (imag)</td>
<td>Pole (real)</td>
<td>Pole (imag)</td>
</tr>
<tr>
<td>5 cm</td>
<td>-77.188728E6</td>
<td>298.312160E6</td>
<td>-55.802917E6</td>
</tr>
</tbody>
</table>

* Real Part in Nepers/s, Imaginary Part in Hz
APPENDIX G

This appendix tabulates the average extracted resonances of the waveforms from the two models of the mine-like target and the small-antenna mine-like target waveforms.

### Table 27
AVERAGE EXTRACTED RESONANCES OF THE MINE-LIKE TARGET

<table>
<thead>
<tr>
<th></th>
<th>Pole (Real)</th>
<th>Pole (Imag)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mine-like Target</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model No. 1</td>
<td>-1.75363970E8</td>
<td>±6.61019133E7</td>
</tr>
<tr>
<td>0.6m Antenna</td>
<td>-5.73125538E7</td>
<td>±1.32122486E8</td>
</tr>
<tr>
<td></td>
<td>-2.87494683E8</td>
<td>±2.27030133E8</td>
</tr>
<tr>
<td></td>
<td>-1.82908509E8</td>
<td>±3.07411043E8</td>
</tr>
<tr>
<td></td>
<td>-9.76454733E7</td>
<td>±4.2847900E8</td>
</tr>
<tr>
<td>Model No. 2</td>
<td>-1.49959862E8</td>
<td></td>
</tr>
<tr>
<td>0.6m Antenna</td>
<td>-9.64575600E7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-2.09351880E8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.91641498E8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.91729062E8</td>
<td></td>
</tr>
<tr>
<td>Model No. 1</td>
<td>-6.90468500E7</td>
<td>±1.31552700E8</td>
</tr>
<tr>
<td>0.15m Antenna</td>
<td>-2.80111200E8</td>
<td>±2.22590300E8</td>
</tr>
<tr>
<td></td>
<td>-2.35432000E8</td>
<td>±2.69826400E8</td>
</tr>
<tr>
<td></td>
<td>-5.03972000E7</td>
<td>±2.99420800E8</td>
</tr>
<tr>
<td></td>
<td>-1.22024400E8</td>
<td>±4.04685600E8</td>
</tr>
</tbody>
</table>

*Real Part in Nepers/s, Imaginary Part in Hz.*

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APPENDIX H

This appendix tabulates the identification results for identification of the mine-like target with the small-antenna system.
<table>
<thead>
<tr>
<th>ANTENNA LOCATION</th>
<th>15 cm, N</th>
<th>30 cm, N</th>
<th>15 cm, E</th>
<th>30 cm, E</th>
<th>15 cm, W</th>
<th>30 cm, W</th>
<th>45 cm, N</th>
<th>45 cm, E</th>
<th>45 cm, W</th>
<th>45 cm, E</th>
<th>45 cm, S</th>
<th>45 cm, W</th>
<th>15 cm, S</th>
<th>45 cm, S</th>
<th>30 cm, S</th>
<th>C</th>
<th>MINIMUM $t_{DL}^* T_{HI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(4T_B)$</td>
<td>0.615</td>
<td>0.821</td>
<td>0.930</td>
<td>0.885</td>
<td>0.906</td>
<td>0.956</td>
<td>0.770</td>
<td>0.743</td>
<td>0.640</td>
<td>0.654</td>
<td>0.659</td>
<td>0.629</td>
<td>0.615</td>
<td>0.625</td>
<td>0.616</td>
<td>0.615</td>
<td></td>
</tr>
<tr>
<td>$(5T_B)$</td>
<td>0.630</td>
<td>0.786</td>
<td>0.303</td>
<td>0.551</td>
<td>0.627</td>
<td>0.915</td>
<td>0.269</td>
<td>0.672</td>
<td>0.410</td>
<td>0.675</td>
<td>0.166</td>
<td>0.569</td>
<td>0.625</td>
<td>0.166</td>
<td>0.615</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(6T_B)$</td>
<td>0.873</td>
<td>0.962</td>
<td>0.670</td>
<td>0.763</td>
<td>0.615</td>
<td>0.922</td>
<td>0.971</td>
<td>0.978</td>
<td>0.917</td>
<td>0.759</td>
<td>0.870</td>
<td>0.788</td>
<td>0.974</td>
<td>0.615</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(7T_B)$</td>
<td>0.938</td>
<td>0.954</td>
<td>0.775</td>
<td>0.956</td>
<td>0.751</td>
<td>0.964</td>
<td>0.978</td>
<td>0.952</td>
<td>0.964</td>
<td>0.825</td>
<td>0.861</td>
<td>0.943</td>
<td>0.994</td>
<td>0.456</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(8T_B)$</td>
<td>0.863</td>
<td>0.935</td>
<td>0.724</td>
<td>0.520</td>
<td>0.718</td>
<td>0.960</td>
<td>0.979</td>
<td>0.881</td>
<td>0.904</td>
<td>0.767</td>
<td>0.820</td>
<td>0.882</td>
<td>0.867</td>
<td>0.420</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(T_B + 8T_B)$</td>
<td>0.76765</td>
<td>0.89153</td>
<td>0.62039</td>
<td>0.63496</td>
<td>0.70538</td>
<td>0.94119</td>
<td>0.9557</td>
<td>0.85055</td>
<td>0.78754</td>
<td>0.73322</td>
<td>0.59436</td>
<td>0.80828</td>
<td>0.85766</td>
<td>0.59436</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{*}$ $t_{MAX}$ = Peak Timing, in units of $T_B$

$^{**}$ $MAX$ = Peak Magnitude, in units of 400 mV

$^{***}$ $E_B$ = Waveform Energy, in units of (400 mV)$^2$
<table>
<thead>
<tr>
<th>n</th>
<th>h(n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1.54267266E-1</td>
</tr>
<tr>
<td>1</td>
<td>-1.6426451E-1</td>
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<td>2</td>
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<td>3</td>
<td>-1.8426453E-1</td>
</tr>
<tr>
<td>4</td>
<td>-2.1426458E-1</td>
</tr>
<tr>
<td>5</td>
<td>-2.2426465E-1</td>
</tr>
<tr>
<td>6</td>
<td>-2.3426471E-1</td>
</tr>
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<td>7</td>
<td>-2.4426476E-1</td>
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<tr>
<td>8</td>
<td>-3.1426485E-1</td>
</tr>
<tr>
<td>9</td>
<td>-3.2426481E-1</td>
</tr>
<tr>
<td>10</td>
<td>-4.4264534E-1</td>
</tr>
<tr>
<td>11</td>
<td>-4.5426451E-1</td>
</tr>
<tr>
<td>12</td>
<td>-6.4264532E-1</td>
</tr>
<tr>
<td>13</td>
<td>-6.5426451E-1</td>
</tr>
<tr>
<td>14</td>
<td>-6.6426453E-1</td>
</tr>
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<td>-7.3426452E-1</td>
</tr>
<tr>
<td>16</td>
<td>-7.4264521E-1</td>
</tr>
<tr>
<td>17</td>
<td>-7.4264521E-1</td>
</tr>
<tr>
<td>18</td>
<td>-9.7426521E-1</td>
</tr>
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<td>-1.2455146E0</td>
</tr>
<tr>
<td>22</td>
<td>-1.3625456E0</td>
</tr>
<tr>
<td>23</td>
<td>-1.4264534E0</td>
</tr>
<tr>
<td>24</td>
<td>-1.5426451E0</td>
</tr>
<tr>
<td>25</td>
<td>-1.6625406E0</td>
</tr>
<tr>
<td>26</td>
<td>-1.7625465E0</td>
</tr>
<tr>
<td>27</td>
<td>-2.0526453E0</td>
</tr>
<tr>
<td>28</td>
<td>-2.1526451E0</td>
</tr>
<tr>
<td>29</td>
<td>-2.2526453E0</td>
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<td>30</td>
<td>-2.5426451E0</td>
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<td>31</td>
<td>-3.03426451E0</td>
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<tr>
<td>32</td>
<td>-3.1426451E0</td>
</tr>
<tr>
<td>33</td>
<td>-3.2426451E0</td>
</tr>
<tr>
<td>34</td>
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<td>35</td>
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<td>36</td>
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<td>37</td>
<td>-3.7426451E0</td>
</tr>
<tr>
<td>38</td>
<td>-4.0426451E0</td>
</tr>
<tr>
<td>39</td>
<td>-4.1426451E0</td>
</tr>
<tr>
<td>40</td>
<td>-4.2426451E0</td>
</tr>
</tbody>
</table>
### Table 30
Determining the Identification Thresholds for the Identification of the Mine-Like Target with the Small-Antenna System Based on FIR Filtering

<table>
<thead>
<tr>
<th>Antenna Location</th>
<th>15 cm, N</th>
<th>15 cm, E</th>
<th>30 cm, N</th>
<th>30 cm, E</th>
<th>45 cm, N</th>
<th>45 cm, E</th>
<th>15 cm, S</th>
<th>45 cm, S</th>
<th>30 cm, N</th>
<th>30 cm, E</th>
<th>C</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_{01})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(T_{01} - 4T_B)</td>
<td>0.579</td>
<td>0.794</td>
<td>0.919</td>
<td>0.866</td>
<td>0.750</td>
<td>0.951</td>
<td>0.659</td>
<td>0.625</td>
<td>0.804</td>
<td>0.594</td>
<td>0.965</td>
<td>0.753</td>
</tr>
<tr>
<td>(T_{01} - 5T_B)</td>
<td>0.568</td>
<td>0.779</td>
<td>0.365</td>
<td>0.527</td>
<td>0.533</td>
<td>0.917</td>
<td>0.725</td>
<td>0.166</td>
<td>0.448</td>
<td>0.800</td>
<td>0.601</td>
<td>0.638</td>
</tr>
<tr>
<td>(T_{01} - 6T_B)</td>
<td>0.85</td>
<td>0.957</td>
<td>0.751</td>
<td>0.761</td>
<td>0.524</td>
<td>0.925</td>
<td>0.852</td>
<td>0.872</td>
<td>0.698</td>
<td>0.971</td>
<td>0.720</td>
<td>0.981</td>
</tr>
<tr>
<td>(T_{01} - 7T_B)</td>
<td>0.935</td>
<td>0.950</td>
<td>0.870</td>
<td>0.471</td>
<td>0.686</td>
<td>0.967</td>
<td>0.903</td>
<td>0.881</td>
<td>0.936</td>
<td>0.993</td>
<td>0.831</td>
<td>0.949</td>
</tr>
<tr>
<td>(T_{01} - 8T_B)</td>
<td>0.885</td>
<td>0.939</td>
<td>0.851</td>
<td>0.543</td>
<td>0.519</td>
<td>0.969</td>
<td>0.746</td>
<td>0.423</td>
<td>0.818</td>
<td>0.856</td>
<td>0.724</td>
<td>0.872</td>
</tr>
<tr>
<td>(T_{01} - 9T_B)</td>
<td>0.76206</td>
<td>0.88358</td>
<td>0.75106</td>
<td>0.63344</td>
<td>0.60214</td>
<td>0.94563</td>
<td>0.77706</td>
<td>0.59332</td>
<td>0.74069</td>
<td>0.84274</td>
<td>0.80818</td>
<td>0.83843</td>
</tr>
</tbody>
</table>
APPENDIX I

This appendix gives detail descriptions of the APU[68] and the micro-program that implements the various system control and target identification processes.

A. The APU and Its Interface with the SDK-80

The connection diagram of the APU is given in Figure 58.

![Connection Diagram](image)

**Figure 58.** Connection diagram for the APU.
Interfacing the APU with the SDK-80 requires the generation of the various control signals. In this study, the APU is interfaced to the SDK-80 as a memory location, and the control signals are generated as follows:

1. **CS**: chip select

   The chip-select signal is generated by using address lines A13, A14, and A15 of the 8080A processor in the SDK-80. The signal generation circuit is shown in Figure 59. The chip-select signal CS is low when the address lines A13, A14, A15 are all high.

   ![Figure 59. The chip-select (CS) signal for the APU.](image)

2. **C/D**: command/data

   The C/D signal is tied directly to the address line A1 of the 8080A processor.

3. **TOR**: tied directly to MEMR of the 8080A processor.

4. **IOW**: tied directly to MEMW line of the 808A processor.

5. **PAUSE**: tied directly to the ready line of the 8080A processor.

6. **CLK**: tied directly to \( \phi2 \) of the 8080A processor.

7. **EACK, SVACK, SVREQ, RESET, END**: unused.

8. To eliminate possible loading problem, two additional signals are generated to inhibit the ROM's and RAM's of the SDK-80 when the APU is being addressed. These two control signals (E1 and E3) are given in Figure 60.
Figure 60. The ROM-inhibit (E1) and RAM-inhibit (E2) signals.
A summary of the APU commands is given in Table 31.

**TABLE 31**

**APU COMMAND SUMMARY**

<table>
<thead>
<tr>
<th>Command Code</th>
<th>Command Mnemonic</th>
<th>Command Description (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FIXED POINT SINGLE PRECISION</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A. 1 1 1 1 0 0 0</td>
<td>SADD</td>
<td>Add TOS to NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>A. 1 1 0 1 1 0 1</td>
<td>SSUB</td>
<td>Subtract TOS from NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>A. 1 1 1 0 1 1 0</td>
<td>SMUL</td>
<td>Multiply TOS by NOS. Result to NOS. Pop Stack</td>
</tr>
<tr>
<td>A. 1 1 1 1 1 1 1</td>
<td>SDIV</td>
<td>Divide NOS by TOS. Result to NOS. Pop Stack</td>
</tr>
</tbody>
</table>

| **FIXED POINT DOUBLE PRECISION** | | |
| A. 1 1 1 1 1 0 0 0 | SADD | Add TOS to NOS. Result to NOS. Pop Stack |
| A. 1 1 0 1 1 0 1 | SSUB | Subtract TOS from NOS. Result to NOS. Pop Stack |
| A. 1 1 1 0 1 1 0 | SMUL | Multiply TOS by NOS. Result to NOS. Pop Stack |
| A. 1 1 1 1 1 1 1 | SDIV | Divide NOS by TOS. Result to NOS. Pop Stack |

| **FLOATING POINT** | | |
| A. 1 0 1 0 1 0 0 0 | SADD | Add TOS to NOS. Result to NOS. Pop Stack |
| A. 1 0 1 0 0 0 1 | SSUB | Subtract TOS from NOS. Result to NOS. Pop Stack |
| A. 1 0 1 0 0 1 1 | SMUL | Multiply TOS by NOS. Result to NOS. Pop Stack |
| A. 1 0 1 0 1 1 1 | SDIV | Divide NOS by TOS. Result to NOS. Pop Stack |

| **DERIVED FLOATING POINT FUNCTIONS** | | |
| A. 1 0 0 0 1 0 0 1 | SVRT | Square Root of TOS. Result in TOS |
| A. 1 0 0 0 0 0 0 1 | SIN | Sine of TOS. Result in TOS |
| A. 1 0 0 0 0 0 1 1 | COS | Cosine of TOS. Result in TOS |
| A. 1 0 0 0 0 1 0 0 | TAN | Tangent of TOS. Result in TOS |
| A. 1 0 0 0 1 0 0 1 | ASIN | Arc Sine of TOS. Result in TOS |
| A. 1 0 0 1 0 0 1 0 | ACOS | Arc Cosine of TOS. Result in TOS |
| A. 1 0 1 0 0 0 1 1 | AATAN | Arc Tangent of TOS. Result in TOS |
| A. 1 0 1 0 0 1 0 0 | LN | Natural Logarithm. Base of TOS. Result in TOS |
| A. 1 0 1 0 1 0 0 1 | EXP | Exponential of TOS. Result in TOS |

| **DATA MANIPULATION COMMANDS** | | |
| A. 1 1 1 0 0 0 0 0 | NP | No Operation |
| A. 1 1 1 1 1 1 1 0 | FIXS | Converts TOS from floating point to single precision fixed point format |
| A. 1 1 1 1 1 1 0 0 | FIND | Converts TOS from floating point to double precision fixed point format |
| A. 1 1 1 1 1 0 1 0 | FLTS | Converts TOS from single precision fixed point in floating point format |
| A. 1 1 1 1 1 0 0 0 | FLTD | Converts TOS from double precision fixed point to floating point format |
| A. 1 1 1 0 1 0 0 0 | CHSS | Changes sign of single precision fixed point operand on TOS |
| A. 1 1 1 0 0 1 0 0 | CHSD | Changes sign of double precision fixed point operand on TOS |
| A. 1 1 0 1 0 0 1 0 | CHSF | Changes sign of floating point operand on TOS |
| A. 1 1 0 0 1 0 1 0 | PTOS | Push single precision fixed point operand on TOS to NOS |
| A. 1 1 0 0 1 1 1 1 | PTDD | Push double precision fixed point operand on TOS to NOS |
| A. 1 1 0 1 0 1 1 1 | PTDF | Push floating point operand on TOS to NOS |
| A. 1 1 0 1 1 0 0 0 | POOS | Pop single precision fixed point operand from TOS. NOS becomes TOS |
| A. 1 1 0 1 1 0 0 0 | POOD | Pop double precision fixed point operand from TOS. NOS becomes TOS |
| A. 1 1 1 0 0 0 0 0 | POPE | Pop floating point operand from TOS. NOS becomes TOS |
| A. 1 1 1 0 0 0 1 1 | XCHS | Exchange single precision fixed point operand. TOS and NOS |
| A. 1 1 1 0 0 1 1 1 | XCHD | Exchange double precision fixed point operand. TOS and NOS |
| A. 1 1 1 1 0 1 1 0 | XCHF | Exchange floating point operand. TOS and NOS |

Note: 1. "A", "B", "C", "D" and "E". These 5 Stack NOS are cleared on stack.
2. All floating point functions double the contents of the stack. Only the result can be counted on to be valid upon command completion.
3. Commands 1, 2, 3, 4, 6, 7, 8 and 11 require that floating point data format be specified (command bits 8 and 6 must be 1).
B. The Microprogram for the Microcomputer System

The various functions of the microcomputer systems are implemented as commands listed in Table 32. The microprogram that implements the various commands is given following Table 32.

**TABLE 32**
**TABLE OF COMMANDS IMPLEMENTED IN THE MICROCOMPUTER SYSTEM**

<table>
<thead>
<tr>
<th>COMMAND CODE</th>
<th>DESCRIPTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Restart</td>
</tr>
<tr>
<td>A</td>
<td>Display a memory waveform on the Oscilloscope</td>
</tr>
<tr>
<td>8</td>
<td>Branch to another ROM</td>
</tr>
<tr>
<td>7</td>
<td>Displays data values of interest</td>
</tr>
<tr>
<td>6</td>
<td>Change or enter the number of waveform taken to form an average waveform</td>
</tr>
<tr>
<td>H</td>
<td>Change or enter number of samples per waveform</td>
</tr>
<tr>
<td>2</td>
<td>Change or enter the sequence number for the next waveform</td>
</tr>
<tr>
<td>1</td>
<td>Initiate Recording sequence via the push button</td>
</tr>
<tr>
<td>0</td>
<td>Record a waveform, and perform the identification process</td>
</tr>
<tr>
<td>B</td>
<td>Dump memory onto tape</td>
</tr>
<tr>
<td>D</td>
<td>Check if data transmission to recorder is error-free</td>
</tr>
<tr>
<td>Source</td>
<td>Statement</td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
</tr>
<tr>
<td>0</td>
<td>THESE ARE THE CASSIETTE TAP MECROCOMPUTER VERSION OF</td>
</tr>
<tr>
<td>1</td>
<td>THE SIX PORTABLE MICROCOMPUTER SYSTEM PROGRAMS</td>
</tr>
<tr>
<td>2</td>
<td>IT IS USED WITH THE MOTHERBOARD UNIT</td>
</tr>
<tr>
<td>3</td>
<td>IT HAS THE ABILITY TO USE DATA PROCESSING</td>
</tr>
<tr>
<td>4</td>
<td>AN ANGEL ADJUST CHIP</td>
</tr>
<tr>
<td>5</td>
<td>THIS PROGRAM PROVIDES A STRONG PULSE FOR THE</td>
</tr>
<tr>
<td>6</td>
<td>FIN CONVERSION AND THE END OF CONVERSION</td>
</tr>
<tr>
<td>7</td>
<td>SIGNAL SIMULTANEOUS THE INTERRUPT HIT PCN</td>
</tr>
<tr>
<td>8</td>
<td>A RELATIVE INPUT SIGNAL ON PCI (LOGIC) SIGNALS THE</td>
</tr>
<tr>
<td>9</td>
<td>PROGRAM THAT THE CARDSCAN IS AT THE BEGINNING</td>
</tr>
<tr>
<td>10</td>
<td>US A NAVEL,</td>
</tr>
<tr>
<td>11</td>
<td>*** MODULES WHICH LINK WITH SINQ'S MEMORY</td>
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<tr>
<td>12</td>
<td>RAM</td>
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************

*** FOR EACH INCOMING WAVEFORM, COMPUTE ***

*** DISPLAY AND STORE PEAK VALUE (ABOVE) ***

*** OR FETCH 1/2 FULL SCALE) AND POSITION. ***

*** OF THIS PEAK 8 TO 7PM). ***

TU FLIP CALL TIME

TPEAK FETCH PEAK VALUE

LDA TPEAK

LVI U0

SLEEP SELECT LEFTMCTOR 2 DIGITS

CALL UPDNHN DISPLAY 2 CONSECUTIVE DIGITS

LDA TPEAK FETCH TIME OF PEAK

CALL UPEECF SELECT PEAK IN CENTER 2 DIGITS

LDA TPEAK FETCH AND STORE VALUE

CALL UPDPFN DISPLAY IN HIGHEST 1 DIGIT

LVI U0

SLEEP IF DIGIT STATUS awk

MVI U0

SLEEP IF ANY KEYPRESS 9

CALL UPEEPM 1 IF NO STAY IN TURFLP MODE

CALL IEP FM YES FETCH VALUE OF KEYPRESS.

CALL UPEECF IF PEA.

CALL UPEEPN IF CLEAR DISPLAY 

CALL UPEEPC IF PEA.

CALL UPEEPF IF FPe.

CALL UPAPN IF PEA.

CALL UPEEPF IF NAPA.

CALL UPEEPG IF PEA.

CALL UPEEPF IF PEAP.

CALL UPEEPC IF PEA.

CALL UPAPN IF PEA.

CALL UPEEPF IF NAPA.

CALL UPEEPG IF PEA.

CALL UPAPN IF PEA.

CALL UPEEPF IF NAPA.
223

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Note: The above code appears to be a listing of machine instructions. The description column seems to indicate the action of each instruction. The code is formatted for a computer that uses assembly language. The meanings of the descriptions are unclear without more context. The code includes calls to procedures and operations on registers and memory locations.
SOURCE: CHPK & CHPK

LIST HELP TO PERFORM THE IDENTIFICATION PROCEDURE AS AN EXPERIMENTAL DATA BANK.

NAME: CHPK

PUBLIC UTILITY

PUBLIC UTILITY:

PUBLIC UTILITY:

PUBLIC UTILITY:

PUBLIC UTILITY:

PUBLIC UTILITY:
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<td>131</td>
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**Notes:**
- SMALL: SMALL UNSIGNED SAMPLE SMALL
- SAMPLE: SAMPLE
- CALL: CALL
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<th>Line</th>
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</table>

**Notes:**
- The text appears to be a listing of instructions or a program, possibly for a computer or electronic device.
- The instructions are written in a combination of English and symbols.
- The context is not clear from the provided text alone.
| 276 | 013 | 7F | 84 | CP | 07F +0E8H +088H +008H |
| 277 | 014 | 6A |     |     |     |
| 278 | 013 | 6B |     |     |     |
| 279 | 012 | 4F |     |     |     |
| 280 | 011 | 7F | 84 | CP | 07F +0C8H +078H +038H |
| 281 | 010 | C1 |     |     |     |
| 282 | 009 | A7 |     |     |     |
| 283 | 008 | 00 |     |     |     |
| 284 | 007 | 00 | 90 | LA | 06H +098H +08CH +048H |
| 285 | 006 | 00 | 91 | LA | 06H +0C8H +08FH +04FH |
| 286 | 005 | 90 |     |     |     |
| 287 | 004 | 90 |     |     |     |
| 288 | 003 | FF |     |     |     |
| 289 | 002 | FF |     |     |     |
| 290 | 001 | FF |     |     |     |
| 291 | 000 | FF |     |     |     |
| 301 | 011 | 00 | 94 | CP | 06H +03FH +07FH +03FH |
| 302 | 010 | 77 |     |     |     |
| 303 | 009 | 77 |     |     |     |
| 304 | 008 | 77 |     |     |     |
| 305 | 007 | 77 |     |     |     |
| 306 | 006 | 77 |     |     |     |
| 307 | 005 | 77 |     |     |     |
| 308 | 004 | 77 |     |     |     |
| 309 | 003 | 77 |     |     |     |
| 310 | 002 | 77 |     |     |     |
| 311 | 001 | 77 |     |     |     |
| 312 | 000 | 77 |     |     |     |
| 313 | 011 | 00 | 97 | UN | 06H +098H +0CC8H +088H |
| 314 | 010 | 77 |     |     |     |
| 315 | 009 | 77 |     |     |     |
| 316 | 008 | 77 |     |     |     |
| 317 | 007 | 77 |     |     |     |
| 318 | 006 | 77 |     |     |     |
| 319 | 005 | 77 |     |     |     |
| 320 | 004 | 77 |     |     |     |
| 321 | 003 | 77 |     |     |     |
| 322 | 002 | 77 |     |     |     |
| 323 | 001 | 77 |     |     |     |
| 324 | 000 | 77 |     |     |     |
| 325 | 011 | 00 | 101 | CP | 06H +0C8H +08FH +04FH |
| 326 | 010 | 00 |     |     |     |
| 327 | 009 | 00 |     |     |     |
| 328 | 008 | 00 |     |     |     |
| 329 | 007 | 00 |     |     |     |
| 330 | 006 | 00 |     |     |     |
C. Details in Obtaining the Second Set of Identification Data With the Microcomputer System

1. Difference equation coefficients

Table 33 tabulates the difference equation coefficients used in the microcomputer system for identification of the mine-like target.

2. Detection thresholds (R_{ID}=30 \, \text{cm})

\begin{align*}
\mathbf{t}_{\text{MAX}} & \quad \text{RANGE} = 14.49 \, (T_{B}) \\
\text{MAX} & \quad \text{RANGE} = 12.82 \\
E_{M} & \quad \text{RANGE} = 0.639, 0.862
\end{align*}

The same detection thresholds were used for identification of the mine-like target in both ground conditions.

3. Identification thresholds (R_{ID}=30 \, \text{cm})

Table 34 tabulates the identification thresholds for identification of the mine-like target in the two different ground conditions.
TABLE 33  
DIFFERENCE EQUATION COEFFICIENTS USED IN THE MICROCOMPUTER SYSTEM  
FOR IDENTIFICATION OF THE MINE-LIKE TARGET

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<th>C</th>
<th>D</th>
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TABLE 34
IDENTIFICATION THRESHOLDS FOR THE IDENTIFICATION OF THE
MINE-LIKE TARGET WITH THE MICROCOMPUTER SYSTEM

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<th>( T_{02} ) T=5TB</th>
<th>( T_{03} ) T=6TB</th>
<th>( T_{04} ) T=7TB</th>
<th>( T_{05} ) T=8TB</th>
<th>(&lt;(n_{T_0})&gt;)</th>
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</table>
APPENDIX J

Table 35 tabulates the extracted resonances and their corresponding residues of the thin-wire (30cm long, 5cm deep) waveform.

Table 35
EXTRACTED RESONANCES FROM THE 30cm LONG, 5cm DEEP THIN WIRE
ANTENNA LOCATION = CENTER OF WIRE

<table>
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<th>POLE * (REAL)</th>
<th>POLE (IMAG)</th>
<th>RESIDUE (REAL)</th>
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<td>.2800813E 9</td>
<td>.1377038E 1</td>
<td>-.2542809E 1</td>
</tr>
<tr>
<td>-.2156001E 9</td>
<td>.7260306E 8</td>
<td>.2210962E 0</td>
<td>.1263321E 1</td>
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<td>-.2800813E 9</td>
<td>.1377038E 1</td>
<td>.2542809E 1</td>
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<tr>
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<td>.3030841E 9</td>
<td>.5459009E-1</td>
<td>.2335131E 0</td>
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<td>.1126777E 9</td>
<td>-.9631155E 0</td>
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<td>-.6272871E 9</td>
<td>.1839096E-2</td>
<td>-.2458968E-1</td>
<td>-.4475425E-7</td>
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</tbody>
</table>

PARAMETERS: N=11, I8S=7, M=2, I11=4, \( \nu = 0.391E-2 \)

Two pairs of poles appear to have dominant residues, namely the pole pairs at 280 MHz and 112 MHz. However, the pole pair at 280 MHz has a much more negative real part, thus, in the late-time region, only the pole pair at 112 MHz is dominant.

Table 36 tabulates the extracted resonances and their corresponding residues from the 30cm long on-surface wire.

In the early-time region, the pole pair at 302 MHz is dominant.

<table>
<thead>
<tr>
<th>* Real Part in Nepers/s. Imaginary part in Hz.</th>
</tr>
</thead>
<tbody>
<tr>
<td>258</td>
</tr>
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</table>
### TABLE 36
EXTRACTED RESONANCES AND FROM THE ON-SURFACE THIN WIRE (30cm LONG). ANTENNA LOCATION = CENTER OF WIRE

<table>
<thead>
<tr>
<th>POLE* (REAL)</th>
<th>POLE (IMAG)</th>
<th>RESIDUE (REAL)</th>
<th>RESIDUE (IMAG)</th>
</tr>
</thead>
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<td>.1591370E 1</td>
<td>-.1711432E 1</td>
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<td>.3023622E 9</td>
<td>.1591370E 1</td>
<td>.1711432E 1</td>
</tr>
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<td>-.1003876E 0</td>
<td>.1049173E-1</td>
</tr>
<tr>
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<td>.4529953E 9</td>
<td>-.2735412E 0</td>
<td>.1113815E-1</td>
</tr>
<tr>
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<td>.6872750E 8</td>
<td>-.6308170E-1</td>
<td>.7273762E-1</td>
</tr>
<tr>
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<td>-.4529953E 9</td>
<td>-.2735412E 0</td>
<td>-.1113815E-1</td>
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<td>.2404006E 9</td>
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<tr>
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<td>-.2077824E-1</td>
<td>-.2096944E-1</td>
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<td>-.2077823E-1</td>
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<tr>
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<td>-.6872750E 8</td>
<td>-.6308170E-1</td>
<td>-.7273762E-1</td>
</tr>
</tbody>
</table>

PARAMETERS: N=13, IBS=5, M=2, II=1, c=0.3839075E-3

*Real part in Nepers/s. Imaginary part in Hz.*