To the Graduate Council:

I am submitting herewith a thesis written by James Carter Hamlett entitled "Nonintrusive Reconnaissance of Cumberland Plateau Soils with Ground Penetrating Radar." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Agriculture Engineering Technology.

Robert S. Freeland, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor
and Dean of The Graduate School

Nonintrusive Reconnaissance of Cumberland Plateau Soils

with Ground Penetrating Radar

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Carter Hamlett

May 1996

To:

My mother, Elaine Hamlett, for her encouragement and support throughout my life. In memory of my father, Bobby Hamlett, for making me who I am. To my sister, Jan Brown, for being my little sister. To my wife, Dody Hamlett, for her love, patience, and support.

Acknowledgments

I would like to extend my appreciation to the University of Tennessee Agricultural Experiment Station, the Department of Agricultural Engineering, and Dr. C. Roland Mote for providing the resources that allowed me to participate in the Agricultural Engineering Program. I also give special thanks to Dr. Robert S. Freeland who served as my major professor. I would never have finished this project without his advise, and friendship.

Thanks are also extended to Dr. Ronald Yoder and Dr. Paul Denton, committee members, for their help and advice.

Thanks are also extended to Dr. Robert D. Freeland, Burton McNeal, and the entire staff at the Plateau Experiment Station. Without their constant help this project would not have been completed.

Special thanks are extended to Carlie McCowan, Darlene Dypolt, Joe Roach, and Gabe Krantz, the NRCS soil survey team in Cumberland County. This research could not have been completed without the soil descriptions that they provided.

Thanks are also extended to fellow students who donated their labor and advice.

The author would like to thank Professor Larry Click and Dr. Reed Cripps, undergraduate professors at Tennessee Technological University, for preparing me not only for the rigors of graduate school, but for the challenges of life. Special thanks are also extended to Walt and Marty Dickson for their encouragement and generosity during my stay in East Tennessee.

Abstract

Evaluation studies were conducted to determine which subsurface characteristics of the Cumberland Plateau could be identified by ground-penetrating radar (GPR). GPR technology offers great potential for non-intrusive mapping of the rhizosphere within this geological region. The Plateau's soil is typically shallow (≈ 1 m), and predominately sandy loam overlaying sandstone bedrock, which is ideal for GPR investigations.

Targeting near-surface events that influence agricultural production, three agricultural fields were extensively surveyed by conventional methods to identify the actual subsurface composition. NRCS soil mapping personnel provided detailed field descriptions at the sites. These data were later used for "ground-truth" referencing during GPR image interpretations.

Survey methodologies using GPR within the Cumberland Plateau region were developed and evaluated. Recommendations, specific for the desired subsurface targets, were made concerning survey procedures, equipment, and settings. Difficulties encountered using the various technologies are discussed along with suggested solutions. Promising agricultural and non-agricultural applications of this technology for this region are presented.

Table of Contents

Chapter Page

List of Tables

List of Figures

Figure Page

Figure Page

Figure Page

List of Abbreviations and Symbols

λ	Wavelength
σ	Relative Dielectric Constant
A/D	Analog to Digital
Ap	Soil Horizon Mixed By Plowing
ATV	All Terrain Vehicle
BC	Transitional Soil Horizon from B to C
Bt	Argillic Soil Horizon
CDP	Common Depth Point
CPT	Common Point Target
Cr	Horizon of Weathered Bedrock
DSP	Digital Signal Processor
EAA	Everglades Agricultural Area
FFZ	First Fresnel Zone
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GSSI	Geophysical Survey Systems Inc.
NRCS	Natural Resource Conservation Service
SIR	Subsurface Interface Radar
TT	Two Way Travel Time

Chapter 1

Introduction and Objectives

1. Purpose

Farmers are requiring highly detailed site-specific information about the soil's subsurface characteristics as global positioning systems (GPS) technologies are introduced into agricultural field production practices. By using GPS-provided field position data, automated field machinery can perform numerous field functions at variable rates. This is accomplished by an on-board computer referencing digital field maps while operating in known positions throughout a field. Thus, fertilizers, seeds, pesticides, and other products or functions can be applied with ultra precision to specific positions within the field at rates that best respond to their corresponding optimized agricultural production practices.

To apply site-specific farming effectively, a great quantity of information concerning the near-surface must be gathered. Often this information is beyond the scope of the traditional soil survey due, in part, to Nature's inherent variability of the near-surface. Ground Penetrating Radar (GPR) shows promise as an evolving subsurface survey tool that will greatly assist with site-specific farming. GPR provides a unique method to nonintrusively collect continuous near-surface data beneath many agricultural landscapes.

Traditional soil surveys were developed primarily to aid agriculture producers in predicting which soils would best respond to farm management practices. The resolution of these surveys was in the order of decameters, and was based largely on the visual surface approximations observed by experts. During the past few decades, the rapid urbanization of certain areas has intensified land use and planning. Many times these urban applications, such as septic systems and waste disposal sites, demand information outside the scope of the traditional agricultural survey. As a result, soil surveys have been periodically updated to meet the demands of urban land use (Miller, 1978; Brown, 1985; Schellentrager et al., 1988).

While the objectives for soil surveys have changed, the methods of obtaining information about soil have remained much the same. Backhoes and hydraulic augers are occasionally used in soil surveys, but the primary tools of the soil surveyor are rock probes, hand augers, and picks (Doolittle, 1987). These labor-intensive, time-consuming, intrusive tools increase the time and cost required to perform soil surveys. Time and cost limit the amount of information that can be collected in the field, therefore limiting the precision of the survey.

GPR technology has advanced to the point that it can provide a unique method of acquiring continuous near-surface data in shorter intervals. Radar has been used to identify argillic and organic horizons in Florida (Collins and Doolittle, 1987). Bedrock radar surveys have been completed on glacial soil in Maine (Collins et al., 1989). GPR has also effectively located the water table in areas with coarse textured soils (Smith et al., 1992).

2. GPR Theory

GPR is a broad band, high frequency, impulse radar designed to penetrate earthen materials (Doolittle, 1987). Short bursts of energy, ranging 10-1000 MHz, are transmitted into the earth by an antenna. These pulses travel through the earth until they strike a layer where the relative dielectric constant of the soil changes. Upon striking this interface, a portion of the radar signal is reflected and refracted, and the remainder continues to penetrate. With greater and sharper changes in the dielectric constant, larger portions of the radar signal's energy are reflected back towards the surface.

Dielectric constant (σ) is a measure of a material's ability to store an electrical charge. This constant can range from 1 to 81 with air being one and water being 81. Dry soil, depending on its composition, has a σ ranging between 2-6. (The dielectric constant and conductivities of several common materials are shown in Table 1.1) Moisture within the soil is the primary factor affecting a layer's σ.

The σ of a soil can be determined by horizontally inserting a metal rod beneath an undisturbed soil layer at a known depth. Two way travel time (TT) of the radar wave reflecting off an object of known depth is recorded by the radar instrumentation. Normally, the radar wave passes through several soil layers having differing σ. If the object's physical depth is known, then an overall dielectric constant to that depth for the surrounding area is generally presumed to be the same, and can be calculated using equation 1.1.

$$\sigma=\frac{(ns/m)^2}{43.56} \qquad \text{(eq. 1.1.)}$$

where

σ= overall relative dielectric constant of the medium
ns = two way travel time of radar wave in nanoseconds
m = distance in meters

Another method of finding the velocity of the radar wave in a medium is the

Table 1.1. Approximate σ and conductivities for several materials (GSSI, 1992b).

Material		ρ mho/m	σ
Air		0	1
Pure water		10^{-4} to $3 * 10^{-2}$	81
Seawater		4	81
Freshwater ice		10^{-3}	4
Granite (dry)		10^{-8}	5
Limestone (dry)		10^{-9}	7
Clay (saturated)		10^{-1} to 1	8 to 12
Snow firm		10^{-6} to 10^{-5}	1.4
Sand (dry)		10^{-7} to 10^{-3}	4 to 6
Sand (saturated)		10^{-4} to 10^{-2}	30
Silt (saturated)		10^{-3} to 10^{-2}	10
Seawater ice		10^{-2} to 10^{-1}	4 to 8
Basalt (wet)		10^{-2}	8
Granite (wet)		10^{-3}	7
Shale (wet)		10^{-1}	7
Sandstone (wet)		$4 * 10^{-2}$	6
Limestone (wet)		$2.5 * 10^{-2}$	8
Copper		$5.8 * 10^{7}$	1
Iron		10^{6}	1
Soil	sandy dry	$1.4 * 10^{-4}$	2.6
	sandy wet	$6.9 * 10^{-3}$	25
	loamy dry	$1.1 * 10^{-4}$	2.5
	loamy wet	$2.1 * 10^{-2}$	19
	clayey dry	$2.7 * 10^{-4}$	2.4
	clayey wet	$5.0 * 10^{-2}$	15
Permafrost		10^{-5} to 10^{-2}	4 to 8

common depth point method (CDP). To apply this method of wave velocity analysis, two antennas and a flat planar reflector are required. One antenna is used as a transmitter and the other is used as a receiver. As shown in Figure 1.1, the two antennas are moved apart equal distances from a common center point. With equation 1.2, the depth to the reflector can be found. After the depth to the reflector is found, the velocity of the wave in the material can be determined by observing the TT of the signal to the reflector when the antenna separation is zero (Ulriksen, 1982).

Ulriksen (1982) also describes the common point target method (CPT) of finding the depth to an object. This method requires one antenna and a point object in the medium. Point objects, such as pipes or rocks, produce hyperbolic reflections. If the antenna moves across such a target as shown in Figure 1.2, the depth z will be a hyperbolic function. With equation 1.3, the depth to a point object can be calculated.

3. Radar Image

A typical graphic profile of a radar scan has three basic parts (Figure 1.3). Part of the radar signal travels directly through the air from the transmitter to the receiver. The top reflection on any radar profile is caused by this direct coupling of the transmitter and the receiver. Reflections from the surface cause the next bands on the graphic profile. These are the first major interface signals on a radar image. Any subsequent events below the surface signal are reflections caused by electrical interfaces within the medium.

The radar instrumentation detects the intensity and the TT of the returning signal. Several of these energy bursts or scans are taken consecutively to form a continuous profile

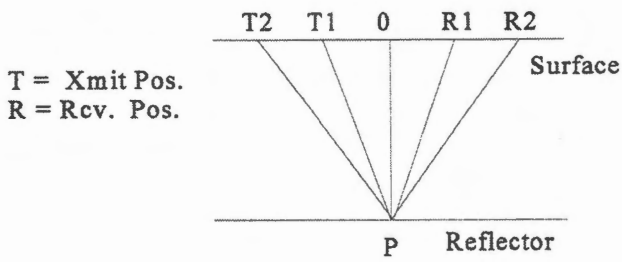

Figure 1.1. Common Depth Point (CDP) method of calculating wave velocity (Ulriksen, 1982).

$$z = \sqrt{\frac{t_2^2 x_1^2 - t_1^2 x_2^2}{4(t_z^2 - t_2^2)}} \qquad \text{(eq. 1.2.)}$$

where,

x = antenna separation
t = TT of radar signal

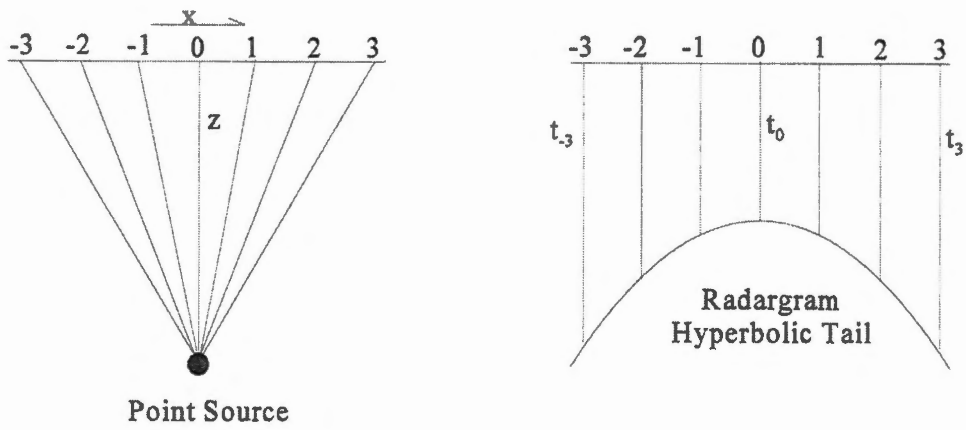

Figure 1.2. Common Point Target (CPT) method of calculating wave velocity (Ulriksen, 1982).

$$z = \frac{|x|}{\sqrt{\frac{t_3^2}{t_0^2} - 1}} \qquad \text{(eq. 1.3.)}$$

where,

x = antenna movement
t_0 = TT at antenna position 0
t_3 = TT at antenna position 3

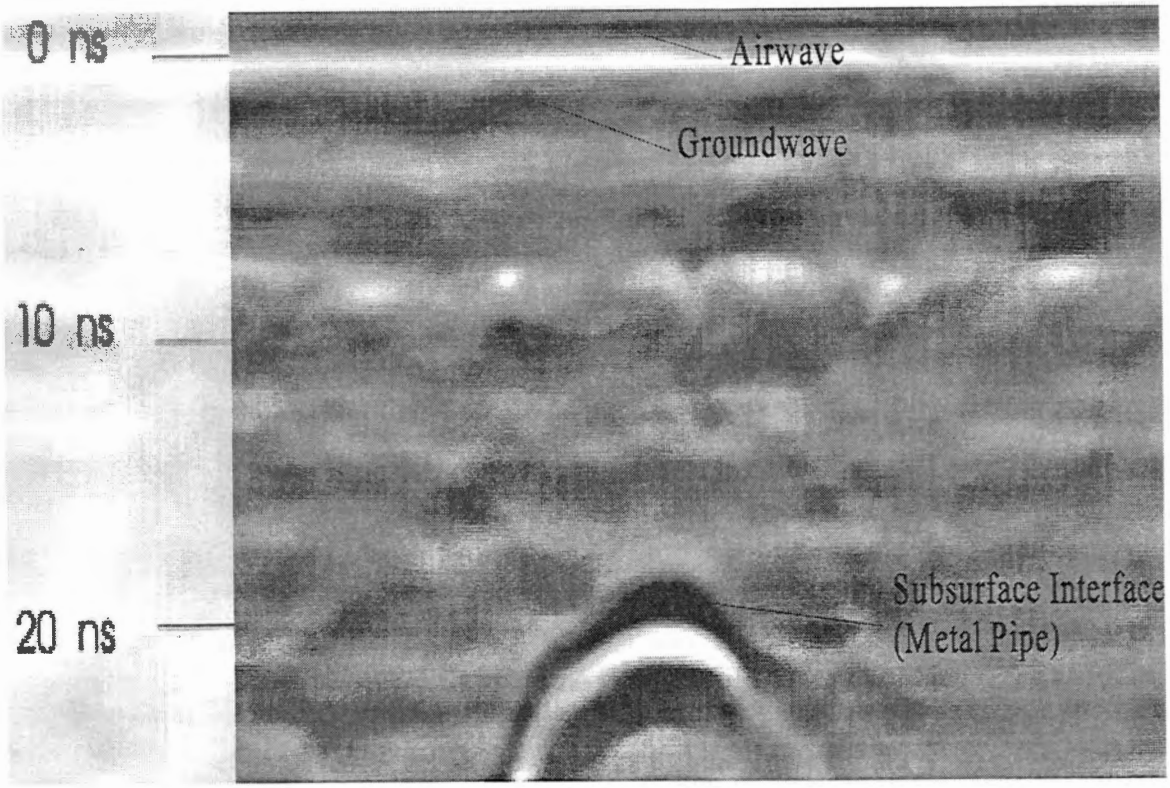

Figure 1.3. Basic characteristics of most GPR data.

of the electrical interface. After being digitized, these signals form images that may be viewed on a monitor, printed, and recorded.

Radar data can be viewed or printed in two formats: wiggle or linescan. A GPR scan in wiggle format consists of lines representing each pulse of radar energy with wiggles or curves in the lines (Figure 1.4). The curves represent subsurface interfaces caused by reflections. High amplitude radar reflections are shown as larger curves and weaker reflections are shown as smaller curves. Geologists and geophysicists commonly prefer the wiggle format because it is traditionally used in seismic surveys. In linescan format, the reflected radar pulses are assigned a color or grey on a scale that ranges from positive to 0 to negative (Figure 1.5). Shades of grey near 0 indicate weak reflections and shades of grey near positive or negative represent strong reflections. Consecutive scans are displayed close together to form a continuous pseudo image of the subsurface interfaces.

4. Unit Settings

The primary operator adjustable radar settings are: antenna model number, range, horizontal filters, vertical filters, range gain, trace position, and display parameters. In depth descriptions of these and the other radar parameters can be found in The SIR System-10A Training Notes (GSSI[1], 1992b) and SIR System-10A User's Manual (GSSI, 1993). By entering the antenna model number, several factory pre-set parameters (scanning rate, samples per scan, etc.) that vary with individual antennas were loaded. Range indicated the

[1]Trade names have been used to provide specific information and do not constitute endorsement by the author, department, or university.

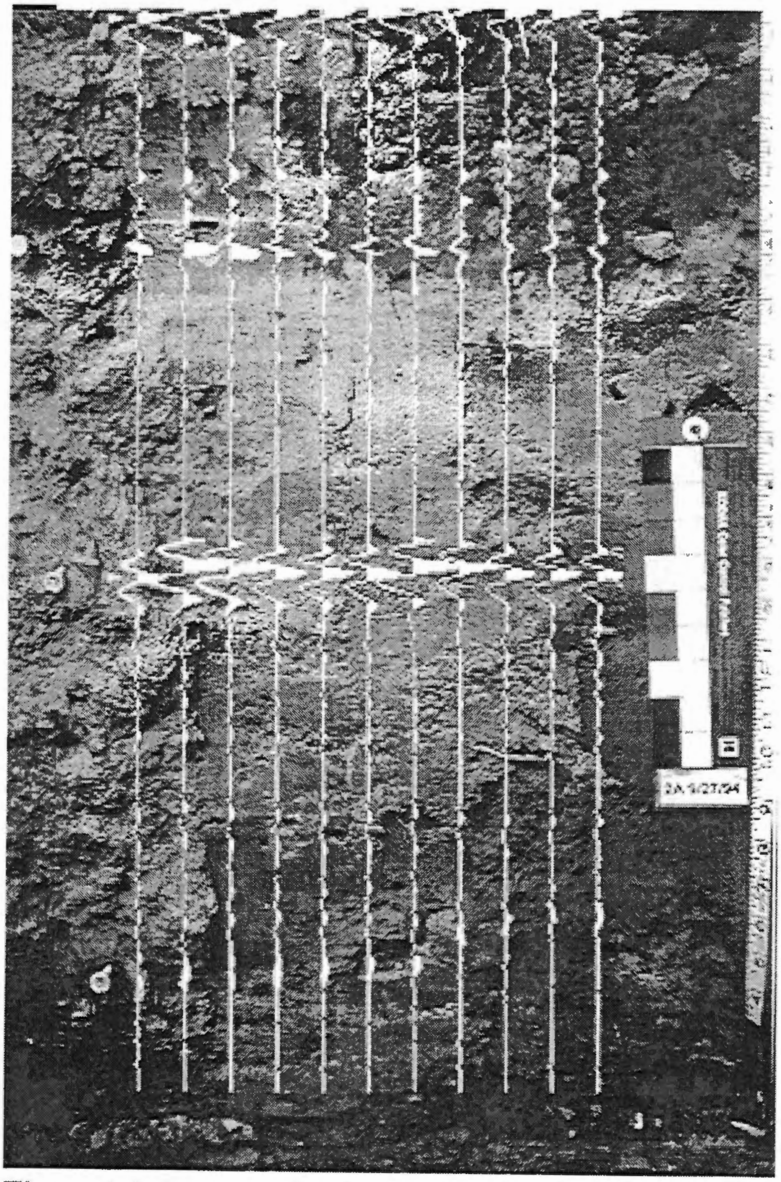

Figure 1.4. An example of radar data displayed in the wiggle format and overlayed on a soil profile.

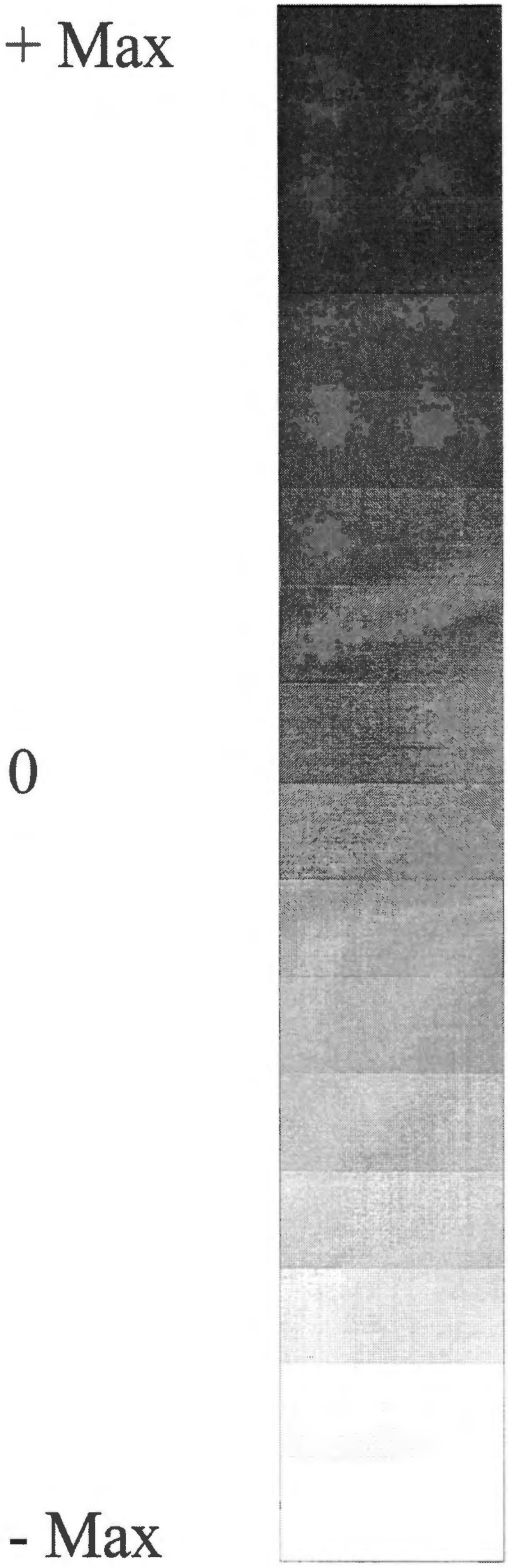

Figure 1.5. Grey scale used with GPR data in this test. Shades of grey near the positive and negative maximum represent stronger radar reflections.

length of time (ns) that returning radar waves were sampled. Selecting a range of 60 ns indicated that the returning radar waves will be sampled for 60 ns after the pulse is emitted. In effect, the survey depth was controlled by the range setting.

Horizontal and vertical filters removed unwanted noise from the radar data. Initial filter levels were set according to procedures outlined in the SIR System-10A Training Notes (GSSI 1992b). IIR high pass filters, which removed low frequency noise, were set at 1/8 the dominant cycles per scan. The IIR low pass filter, which removed high frequency noise, was set at two times the dominant cycles per scan. The dominant cycles per scan was calculated as the survey range divided by the antenna pulse width. Depending upon soil type and conditions in the field, minor adjustments to the filter settings were made to optimize data quality.

Range gain indicated the amount of amplification applied to the returning radar signal at specific time intervals after the radar pulse was emitted. The trace position, or start of scan, can be set such that any reflection in the radar image appears at 0 ns. By setting the trace position with the ground wave at 0 ns, the soil surface appeared at the top of the radar scan and, with the proper σ, the TT to subsurface interfaces was converted to depth. Two display parameters were available: linescan and wiggle format. Within linescan several different color charts or grey scales were available.

5. Penetration Depth and Resolution

Penetration depth of a radar wave is limited by several factors. First, the electrical conductivity of the medium affects the attenuation (i.e., decay) of the wave's energy.

Penetration is also limited by the number and strength of electrical interfaces within the medium. Another factor that limits penetration is the angle at which the radar waves travel from the antenna into the earth. Finally, penetration is affected by the wavelength of the antenna used.

Conductivity of the medium is the primary factor affecting the possible penetration depth of the radar wave. Penetration of the radar signal is restricted by highly conductive mediums (i.e., wet clay, soils having high salinity). Materials having lower conductivities (i.e., dry sand) allow greater penetration.

Penetration depth is limited by the number and strength of electrical interfaces within the medium. A large number of interfaces or very strong interfaces will reflect more of the radar signals to the surface and reduce the depth of penetration. Materials with few interfaces allow the signal to continue traveling downward increasing the penetration depth.

The angle at which the radar signal enters the medium also eventually limits penetration depth. The wave enters the material in the shape of a cone. As the depth of penetration becomes greater, the area covered by the cone becomes larger. Data collected by the radar system is reflected from a small area within this cone known as the First Fresnal Zone (FFZ) (Figure 1.6). Penetration is limited when the cone becomes so large that sufficient signals are not reflected from the FFZ to form a radar image. Even though the medium upon which the antenna is operated affects the angle at which the radar waves travel, equation 1.4 can be used to approximate the radius of the FFZ (GSSI, 1992b):

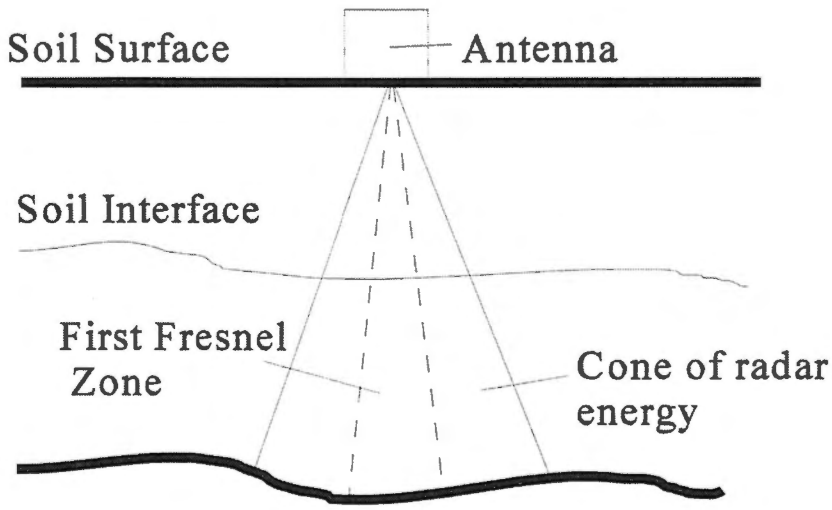

Figure 1.6. Simplified radiation pattern of radar waves and the First Fresnel Zone.

$$R_F = (\lambda\, r_0 + .25\, \lambda^2)^{0.5}$$

(eq. 1.4.)

Where: R_F = Radius of First Fresnel Zone

λ = Wavelength

r_0 = Depth to target

Resolution (defined as the width of a layer that can be identified within a radar image) and penetration depths are affected by the wavelength (λ) of the radar signal. Antenna selection by the operator controls λ. Antennas transmitting high frequencies (i.e., smaller λ) can resolve very thin layers. However, a small λ limits the depth of penetration. An antenna having a lower frequency (i.e., larger λ) cannot resolve as narrow layers as higher frequency antennas, but its signals can penetrate more deeply than the higher frequency antenna.

A typical radar system consists of a control unit, an antenna, and a printer or recording device. Control units are constructed both as a separate unit or within another piece of the system. This unit controls factors such as measuring time, scanning speed, filtering, and amplification. In digital units, real world analog data are converted to binary numbers. Data stored in this format can be amplified and filtered during post processing.

6. Objectives

An evaluation study was performed on the Cumberland Plateau in Cumberland County, TN at the Plateau Experiment Station using GPR. Antennas rated at 900 and 500 MHz were used with a Subsurface Interface Radar System 10A (SIR System-10A) manufactured by Geophysical Survey Systems, Inc. (GSSI), North Salem, NH. For three sites on the Cumberland Plateau, this study had the following objectives:

1. To identify the subsurface characteristics that can be resolved using GPR,
2. To design, develop, and evaluate GPR survey methodologies for the Cumberland Plateau region, and
3. To formulate recommendations, specific for the desired subsurface targets, concerning survey procedures, equipment and settings.

Chapter 2

Literature Review

1. GPR Capabilities

Kung and Lu (1993) conducted a test to determine the accuracy of GPR in detecting flat and inclined layers with different σ than the surrounding material. PVC plates were placed in a diving tank filled with water. The plates represented layers of differing σ within the soil. The goal of the first test was to find the depth to and boundaries of the flat plates. In the second test, the objective was locate boundaries and depth of plates that were inclined. Electrical conductivity of the water was evaluated in the third test. All tests were conducted with an EKKO IV radar and a 450-MHz antenna.

Test one showed that the TT of the radar waves to the flat plates had a linear relationship with the plate's depth. This finding suggests that once the radar is calibrated, the depth to a flat object can be found. Plate edges were also accurately found with the GPR unit. In the second test, inclined plates could be found and the depths predicted. Due to the inclination of the plates, much of the radar energy was reflected away from the antenna. Because of this, the edges of the inclined plates could not be accurately located. Test three showed that the depth and inclination of the plates could be found when the conductivity of the water was increased. Conductivity was increased by adding salt. Because of the higher conductivity of the water, the radar signal was attenuated more rapidly. Rapid attenuation led to less penetration by the radar pulse.

Kung and Lu (1993) noted that finding boundaries and predicting depth to horizons within soil would be much more difficult than finding objects in a homogeneous medium such as water. With a homogeneous medium, the radar wave traveled at a constant velocity. In soils, several horizons with differing conductivities could be present. This would cause the velocity of the radar wave to change. To predict depth to an object under these conditions, the radar would have to be calibrated at several depths.

Kung and Lu (1993) also stated that mediums with high σ, such as water, cause the radar wave to spread from the antenna in a small cone. Sandy soils, with a much lower σ, allow the radar wave to spread into a much larger cone. With the larger cone, more area is scanned and boundaries of objects would be more difficult to find.

Doolittle (1987) has determined that GPR does not work well in all soils under all conditions. Penetration depths vary with the soil type. Typically, Doolittle (1987) found that his equipment provided penetration depths in coarse textured soils of 5-25 m, 2-5 m in moderately coarse textured soils, 1-2 m in moderately fine soils, and <0.5-1.5 m in fine textured soils. The electrical conductivity of the soil is the biggest factor in determining how deeply the radar will penetrate. The radar wave is attenuated much more rapidly in soils with high conductivity. Moisture, salts in solution, and the amount and type of clay present in the soil determine the soil's conductivity.

Johnson et al. (1979) noted that the depth of penetration of the radar wave depends upon the type of soil and the water content of the soil. A saturated soil would attenuate the signal more rapidly, and penetration depths would decrease. High percentages of silt and clay rapidly attenuate the radar signal thus restricting penetration. Soils high in salts also restrict the penetration of the radar signal. Saturated soils with low conductivity may allow fair penetration.

Strong radar reflections are usually created by abrupt changes in soil texture, density, and moisture content. Doolittle (1987) has effectively found argillic horizons on the Atlantic and Gulf Coastal Plains of the United States. He used GPR to locate horizons differing in degree of cementation, bulk density, or consistency. Sedimentary bedrock with layered structure can usually be found with GPR. Bedrock with an irregular surface provides more complex reflections that are harder to interpret. Doolittle (1987) successfully used GPR to find the water table in coarse textured soils. As the texture becomes finer, the capillary fringe increases. This reduces the dielectric contrast between the soil above and below the water table making it more indistinct on the radar image. Radar has also been used to resolve horizons of differing chemical or organic content in Florida.

Physical data (ground truth) are required for all GPR surveys. Doolittle (1987) explained that information from a few soil borings is compared and correlated to the radar image to identify images within the radar data and to provide a depth scale. After correlation, depth and lateral continuity of soil horizons were found from the radar data. When soil characteristics change or new horizons appear, soil borings were taken again to recorrelate the radar image. Ground truth borings contained some inherent inaccuracy. Because of this, slight differences appeared between the ground truth data and the radar data.

GPR provides continuous, nondestructive data on subsurface features with contrasting σ. Studies with GPR have been conducted in the Georgia Coastal Plain region at the South East Watershed Research Laboratory (SEWRL) since 1983 (Truman et al., 1994). The researchers have determined that radar can effectively monitor subsurface horizons that have contrasting dielectric properties. The depth and lateral extent of subsurface features can accurately be found with GPR. Researchers at SEWRL also found that GPR was useful for mapping lake and stream beds. The researcher found that the vertical closeness of the soil horizons, iron content of the soil, moisture content, and the capillary fringe of a fine textured soil limit the performance of GPR.

2. GPR Calibration

Johnson et al. (1979) explain that the vertical scale of the profile produced by radar was based on the TT of the radar wave. The TT could be converted to depth if the dielectric constant of the medium was known. TT could also be converted to depth if an object of known depth was found for calibration. The horizontal scale depended upon the speed at which the antenna was towed and the output rate of the screen or printer used to view the data.

A simple method of calibrating a radar system was tested in two soil types (Zobeck et al., 1985). Soils from each soil type were sampled from large pits. The first soil type was well drained and on a 18% slope. This soil was colluvial and contained more than 35% fine-grained sandstone coarse fragments. The second soil type was moderately well drained on a 2% slope and was developed in loess over Wisconsonian glacial till. Radar scans were taken both before and after a 4.5-cm bucket auger was placed in the side of the pit. After printing the data, an engineering ruler was used to measure the distance to the auger on the radar graph. By comparing the distance to the auger on the radar data (A) to the known depth of the augers (B), the unit was calibrated. Dividing B by A created a ratio to interpret depth from the radar data. To calculate depths to unknown markers, the distance to the object on the radar data was multiplied by the ratio. This type of calibration was accurate for determining depth within 6% (3 cm) in the soils studied. Changes in moisture content or texture of the soil would change the depth ratio and recalibration would be required.

In another test, four methods were used to calibrate a GPR system to find depth to the water table (Smith et al., 1992). As a ground truth, water depth at 28 shallow wells was measured. First, the depth to the water table in a single well was used for calibration. Next, the depth at three wells was used. Third, the water table depth at six wells was used. Finally, the known depth to buried metal pipes in unsaturated soil was used as a calibration for the radar.

The vertical scale on the radar data changed drastically as the soil became more saturated. As the water content increased, the σ increased resulting in an expanded vertical scale on the radar data. This caused the depth calibrations based on the pipes buried in nonsaturated soil to under predict the depth to the water table. Calibrations based on one, three, and six measured depths to the water table at different wells all produced accurate predictions of the depth to the water table. Depth predictions based on three wells provided data that were as accurate as that based on six wells.

Based on calibrations made on the buried pipes, radar under predicted the water table (Smith et al., 1992). Predictions of pipe depth based on calibrations made on the measurements to the water table over predicted the depths of the pipes. This indicates that the radar image is reflecting off a zone above the water table in which the water content of the soil is rapidly changing. Predictions based on the reflection from the capillary fringe can be used as long as the actual water table was used to calibrate the data. These predictions can only be made in areas of similar soil. Changes in soil type would change the extent of the capillary fringe and negate the calibration.

3. Soil Surveys

Variability in depth to spodic and argillic horizons was tested in an Atlantic Coast Flatwoods area in north central Florida with GPR (Collins and Doolittle, 1987). The soil series studied was a Sapelo. In a Sapelo soil, a spodic horizon at a depth of 25-76 cm and an argillic horizon at a depth of 100-178 cm must be present. Depths to the argillic horizons were highly variable in this region. With more than 2 m of penetration and adequate resolution of the features, the 120-MHz antenna used in the test was effective. Data were taken at 110 discrete points. Depth ratios for the radar imagery were found by auguring to the horizons at four locations. Depth to the spodic horizon was 27-34 cm. Intensity of the reflected radar signal could be inferred as changes in the vertical properties of the soil. The more abrupt the change the greater the reflected signal. As the organic content of the spodic horizon decreased, the strength of the reflected radar signal also decreased. The GPR image of the argillic horizon was variable in contrast and in depth. At all observation sites, the spodic horizon was within the established range for the Sapelo series. However, the mapped level of the argillic horizon was too shallow at 21% of the sites tested.

The researchers also showed the efficiency of using GPR for soil surveys in this test. Collection of 110 data points in the field required only 30 min. Scaling of the radar data also took 30 min. If a soil scientists spent just 5 min at each site with a bucket auger, the survey would have taken around 9 h.

In another study, the variability of soil horizons and other soil properties was investigated with GPR (Truman et al., 1988). Conducted on the southern coastal plain of Georgia, the researchers had two goals. Finding the effectiveness of GPR in detecting argillic horizons and the water table was the first goal. Evaluation of spatial variability of these features with GPR was the second goal. Radar data for the test were taken with a SIR System-8 control unit produced by GSSI and a 120-MHz antenna. Three sites on the Georgia coastal plain were used for the study. These sites contained several soils of the following series: Dothan, Pelham, Fuquay, Troup, Ocilla, Tifton, Albany, and Kershaw. Pits were dug in a representative soil at each site. These pits were used to obtain soil samples and to insert metal rods into the soil for calibration and reference points. GPR successfully resolved argillic horizons. Higher water holding capacity of the clay horizon resulted in higher dielectric constants and produced a radar reflection. GPR revealed changes in the depth to the argillic horizon. The relationship between the ground truth depth and the depth determined by GPR data was linear with a correlation coefficient of 0.94.

At two locations in central Florida, Johnson et al. (1979) conducted a test to find the possibility of using GPR for soil surveys. Sites containing a variety of soil series were selected by the Soil Conservation Service in Polk County and Hardee County Florida All radar data were gathered with 300- and 900-MHz antennas and a GSSI mainframe.

For this test, radar generally identified key soil horizons. Many subtle changes, such as a slight change in texture, were not identifiable with the radar. Usually, changes from albic to spodic and argillic horizons were identifiable. Details near the surface were not studied in this test but the use of a high frequency antenna could make this possible. When the horizons were uniform, the radar data and ground truth data correlations were as close as ±2.5-5 cm.

Results of this test showed that GPR could be used to identify certain soil horizons. The lateral extent of these horizons could also be mapped using the unit. Ground truth borings were necessary to establish a correlation between the soil and the radar data. The unit could also locate abrupt changes in the soil not evident on the surface. By using radar to find these changes, soil scientists can determine the proper locations for borings. By doing this, accurate soil descriptions can be obtained from a limited number of borings.

Johnson et al. (1979) noted that antenna selection is crucial to the success of soil surveys with GPR. Low frequency antennas provide the greatest penetration but lack resolution. High frequency antennas cannot penetrate as deeply but can resolve boundaries that are closer together. GPR units with the ability to use a variety of antennas should be chosen for soil surveys.

GPR was used to update soils that had been previously surveyed in Hillsborough, Orange, and Seminole Counties Florida (Schellentrager et al., 1988). A SIR System-8 with a 300- and 120-MHz antenna was used to conduct the surveys. The test was conducted by first separating the survey area into cells. GPR was then used to investigate map units in each cell. This method assured that each area was equally sampled. Transects were selected before entering the field. This prevented biases of the soil scientists from affecting the test. Each transect averaged 305 m and contained 10 equally spaced observational markers. In most cases, one soil boring was sufficient to identify the diagnostic subsurface horizons. The test resulted in a general reduction in the number of map units. As a result of the GPR survey, several soil series were renamed. For example, the Plummer series occurs in a thermic temperature regime and has an argillic horizon at a depth of 1-2 m. GPR data in an area previously labeled Plummer showed that the argillic horizon did exist but that its depth was highly variable and commonly was deeper than 2 m. The series was then renamed. In areas where GPR performs properly, it was an effective tool for updating soil surveys.

A test was conducted to find the usefulness of GPR units in mountainous terrain (Olson and Doolittle, 1985). The test was conducted at the Mill Run watershed at the eastern edge of the Appalachian Highlands in northwestern Virginia. A SIR System-8 with both 120- and 300-MHz antennas were used in the study. The test was conducted in loamy-skeletal, siliceous, mesic Typic Dystrochrept soils. Interpretable data on the soil profiles were provided by the radar unit to depths of 2-3 m. As the depth increased, more processing was required to interpret the data. Though radar has been used to find water tables in areas of coarser material, the researchers were unable to differentiate this characteristic in this test. This was due to the large capillary fringe in the fine textured soil. Argillic horizons and fragipans were found with the GPR unit. In most areas, higher clay contents reduce the penetrating ability of the radar. In this area, the lower exchange capacity of the clays allowed favorable radar responses to 2 m or more.

Shih and Doolittle (1984) used a SIR System-8 to investigate the thickness of the organic soil. Antennas with the following frequencies were used for the study: 120, 300, and 500 MHz. Because of the pitted limestone bedrock, comparison between the ground truth data and the radar data was difficult. To compensate for this, the researchers took four physical measurements within 25 cm of each checkpoint and found an average for the checkpoint. The profile created with the radar was then compared with the average of the physical measurements at each checkpoint. Soil thickness found with radar was within 8 cm of that found with physical probes 91% of the time.

Changes in soil map unit composition in the Everglades Agricultural Area (EAA) in the Florida Everglades were studied with GPR (Collins et al., 1986). Intensive cultivation brought on the need to reexamine the soils. GPR data for the test were gathered with the same radar system used by Shih and Doolittle (1984) and a 120-MHz antennae. GPR data showed that the organic soils in the EAA have been decreasing. This fact affects many management decisions that are based on organic thickness in the EAA.

4. Bedrock Surveys

In upland areas of New England, predicting the depth to bedrock from the soil landscape is often difficult. Mechanical means of finding the depth to bedrock are also difficult in deep (1 m) to very deep soils (>1 m) due to rock fragments and dense layers that stop probes (Doolittle et al., 1988). Systematic sampling with conventional tools is also slow, and labor intensive. With GPR, a site can be systematically sampled by fewer people in less time.

Knowing the depth to bedrock is important. Many soil series are differentiated by the depth of the soil. Shallow soils restrict root penetration, affect the percolation of water and the absorptive capacity of effluent, as well as affecting the cost and difficulty of excavation. GPR can be used to aid in soil-landscape relationships and as an aid in mapping soil depth.

Depth to bedrock in the New England soil was irregular. The researchers noticed that areas of fractured bedrock produced complex radar images that were difficult to interpret. Smooth bedrock surfaces produced continuous easily interpretable radar images. In areas with high concentrations of bolders or stones, the radar images were complex and the bedrock boundary was difficult to find.

Another test was conducted in Hancock County, MN to find the variability of the depth to bedrock and to compare data taken with GPR verses conventional sampling methods(Collins et al., 1989). Soil types in many areas are determined by the depth to bedrock. Finding the depth to bedrock by conventional methods is difficult in glaciated landscapes due to rock fragments that restrict the penetration of mechanical probes. A SIR System-8 with a 120-MHz antenna was used for the test. The radar system provided detailed interpretable data for the test. Bedrock depth was highly variable in the test plots with depths of 28-173 cm. Radar images were complicated by certain conditions. Broad transitions from stony deposits to bedrock produced weak radar reflections. Fractured bedrock also produced complex images. Depth to bedrock data taken with the auger and that taken with GPR did not always agree. At the first test site, the data were in very close agreement At the second, site the data was statistically different.

Depth to bedrock measurements taken with soil augers have an inherent amount of error. Due to the irregularity of the landscape it is never known if the auger is stopped by a rock fragment or bedrock. Due to the lack of agreement between data in the second plot, a trench was excavated. Eighty seven percent of the scaled imagery was within 0-10 cm while 68% of the augured data varied by more than 28 cm. It was discovered that the augured measurements were restricted to 1 m due to a dense layer of rock fragments. Had the bedrock been deeper, the augured data would have been even more inaccurate. Approximate depth to the dense rock fragments was revealed by the augured data. In conclusion, GPR can be used to find the depth to bedrock and the composition of soil map units based on depth to bedrock. The correlation between GPR data and actual depth to bedrock on the glaciated terrain was high, while the data taken with a soil auger was questionable.

5. Wetting Fronts and Water Tables

The vadose zone is the unsaturated portion of the soil and is very important in the hydrological cycle. A good knowledge of this zone and water movement through it is required to assess the potential damage done to the soil and ground water by human activities. Water movement through the vadose zone would reveal the path taken by chemicals and waste to the ground water.

GPR was evaluated as an instrument for monitoring wetting front movement through the vadose zone of a sandy soil (Vellidis et al., 1990). Tests were conducted in the Coastal Plain physiographic region near Tifton, Georgia with a SIR System-8 and a 120-MHz antenna. The soil at the test site was classified as a Lakeland Sand and the depth was 1.9-4.4 m. Clay restricting layers were present and caused perched water tables under wet conditions. A 12 X 12 m grid with labeled markers at each point was used for the test. A sprinkler system on risers was in place in a 24-m grid. The sprinkler system was designed to produce 12.5 mm/h of water.

Two tests were run. In the first test, a 125-mm application of water was applied. GPR transects were conducted before irrigation and 1 h, 4 h, 7 h, and 25 h after the irrigation event. Soil samples were collected after each of the GPR surveys. The second test consisted of a 100-mm irrigation followed by GPR transects prior to and in three hour intervals following the wetting. The final transect was made 25 h after the irrigation. Collection devices on the soil surface were used to collect water to find the uniformity of the water distribution. Water collected was used to develop uniformity curves for the sprinklers. Vellidis et al. (1990) found that the uniformity curves mirrored the GPR data. In areas with large applications of water, the penetration of water into the soil was also the greatest. After 25 h, the wetting front was barely visible on the radar image. This shows that the boundary between wet and dry soil was becoming less distinct. Due to the characteristic three band image produced by GPR, the band that represented the leading edge of the wetting front was difficult to find. The researchers found that the central band may be the leading edge of the wetting front but further investigation was recommended.

Vellidis et al. (1990) concluded that GPR could be an excellent tool for detecting the wetting front in the vadose zone of sandy soils. GPR images were clear and closely matched the application uniformity curves. Water content of the soil provided by soil samples also supported the data found with the radar. A statistical link between the radar image bands and the wetting front was found but more research was recommended. This research could be very important in determining paths of preferential flow of agricultural chemicals and other man made pollutants.

In another study, the ability of GPR to detect changes in the position of a water table in sandy soils was evaluated (Smith et al., 1992). Data was taken with a SIR System-8 and a 120-MHz antenna in the Coastal Plain region near Tifton, Georgia. Test plots consisted of Lakeland Sand soils with depths of 1.9-4.4 m. The soil contained a layer of high clay content that forms a transient water table during high rainfall periods. Depth to the water table was measured with an accuracy of 3 mm at 28 shallow wells placed on the test site in a 12 X 12 m grid. GPR was accurate in predicting the depth to the water table based on a few monitoring wells. The predictions based on buried objects were not accurate. The researchers recommend more work with shallower water tables and higher frequency antennas to decide if both the water table and the capillary fringe can be observed

In a test conducted by Johnson et al. (1979) in Polk and Hardee counties Florida, GPR did not consistently identify the water table. This is due to the capillary fringe caused by the soil pores. This fringe did not produce a distinct dielectric boundary for the radar signal to reflect off. However, in coarse soils where the boundary was more prominent the water table could be resolved.

In a study conducted on the southern coastal plain of Georgia, Truman et al. (1988) failed to consistently locate the water table in fine textured soils. Dothan, Pelham, Fuquay, Troup, Ocilla, Tifton, Albany, and Kershaw soils were contained within the three test areas. Fine textured soils cause the water table to be difficult to identify. Due to the capillary fringe, the gradual change from dry soil to the water table caused a gradual change in dielectric constant and produced a weak radar reflection. Course textured soils of the Kershaw series produce distinct water tables that could be resolved with GPR. A linear relationship between measured depth and the depth determined by GPR was 0.98.

GPR was used to survey karst areas in Pinellas, Hillsborough, and Hardee counties in west-central Florida (Barr, 1993). A SIR System-8 with a dual 80-MHz antenna was used for the study. GPR was reported as a relatively inexpensive, nonintrusive method to define shallow lithologic and hydrologic contacts. Shallow investigations were all that were possible in areas underlined by clay. However, greater depths were possible in areas composed primarily of sand. Penetration depths ranged from 1 m to as much as 15 m. GPR was used to detect sediment thickness, find depth to the water table, clay beds, and buried objects. Radar was also used to identify sinkholes and karst development, and to profile lake bottom structure. Subsurface deformation features were found with GPR in areas where surface depressions were observed and in areas where they were not visible. Barr (1993) found that the quality of the data depended on several things. These included the user's knowledge of the equipment and of the hydrogeologic conditions of the area. The ability to interpret the data also depended on the sharpness of the contrast of the subsurface materials.

Chapter 3

Materials and Methods

1.Equipment Description

Throughout this study, ground penetrating radar data were collected using a SIR System-10A. This instrument was manufactured and marketed by GSSI, Inc. (North Salem, NH, USA). Components obtained from GSSI included a PC-compatible data acquisition and control unit (Figure 3.1), a 15-m antenna control cable, and various antennas. Interchangeable GSSI antennas were chosen by the operator for connection with the radar system unit. Antenna selection was based on the survey requirements and site conditions.

Radar System Unit

The SIR System-10A unit enclosure (44.1 cm x 38.1 cm x 17.8 cm) housed a 486SLC Cyrix motherboard having an 80387 math coprocessor. Employing a 20-MHz Motorola DSP-56001 digital signal processor (DSP), the high speed signal processing board was an integral component. Proprietary system software was stored in firmware, which automatically executed upon system powering. Typically, this software controlled the radar system during field operation.

System firmware (i.e., the control program) was updatable using a system diskette. The system could also boot MS-DOS and run compatible DOS software from the internal 3.5-in., 1.44-MB diskette drive, or from an optional, external SCSII hard drive. PC industry-

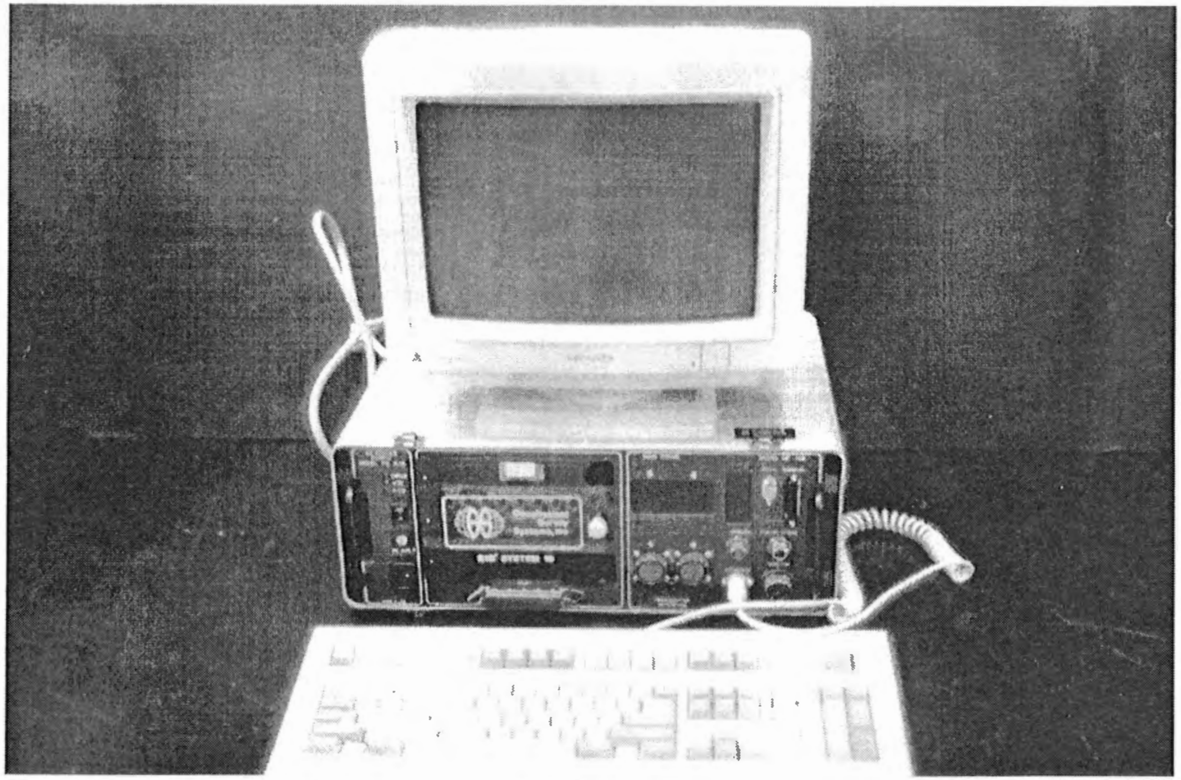

Figure 3.1. GPR control unit, monitor, and keyboard.

standard serial, parallel, keyboard, and SCSII ports were provided. These ports were mounted externally on the front face of the chassis.

Radar analog signal returns were digitized using a high-speed Analog-to-Digital Converter (A/D) within the SIR System-10A unit. Hardware and software filters, along with time-dependent range gain settings, supplied exceptional signal processing flexibility during data acquisition or later analysis. Through the radar system, special markers were manually placed in the data stream when the antenna was moved past field survey flags or events, supplying horizontal scaling within the stored data.

Data Storage

The motherboard held 16-MB of RAM that were available for program execution and data storage. Temporary data storage and rapid playback were accomplished with the majority of memory above the DOS 640-KB boundary. Data, when recorded for later analysis, were written directly to tape via an internal 2.3-GB Exabyte 8-mm tape drive. Sequential writing to the tape during field operation was fast; however, seek access of the tape for playback was slow. After a field survey, data were retrieved from tape and stored in MS-DOS file format using an optional 1-GB SCSII external hard drive.

Monitor and Keyboard

GSSI marketed a combined monitor and keypad in a rugged case that was powered by an external 12-V power source, allowing mobile operation by using an vehicles's power supply. To significantly reduce equipment costs, an inexpensive VGA color monitor was used for the display. A standard AT keyboard provided operator input and control.

Power

GSSI provided two input power options for their SIR System-10A units, 12 VDC or 110 VAC. The 12-VDC option was often favored by their customers for field use where vehicular power could be tapped easily. However, this option also required an AC/DC converter when powered in the laboratory for data retrieval, data analysis, or testing.

A mobile 110 VAC system was opted for instead, using a Model PV 1200 FC Tripp-Lite DC/AC Power Inverter (Figure 3.2) and two Exide Nautilus Gold deep cycle marine 12-VDC batteries, which were wired in parallel. Twelve hundred watts of AC power in a regulated, modified sine wave were supplied by the inverter to power both the system unit and the VGA monitor. Sufficient reserve power was stored to allow surveying over an interval that exceeded 6 h between battery recharge. Both the batteries and power inverter were transported in a small, plastic two-wheel cart (Figure 3.3). By mounting the power system in a mobile cart, the power source could be contained, moved about, and operated from a variety of vehicles.

Antennas

Numerous antenna models, ranging 60-1000-MHz and manufactured by GSSI, were compatible with the SIR System-10A. Constructed in a flat bow tie configuration, GSSI antennas were mounted in rugged non-metallic housings having two military-type external

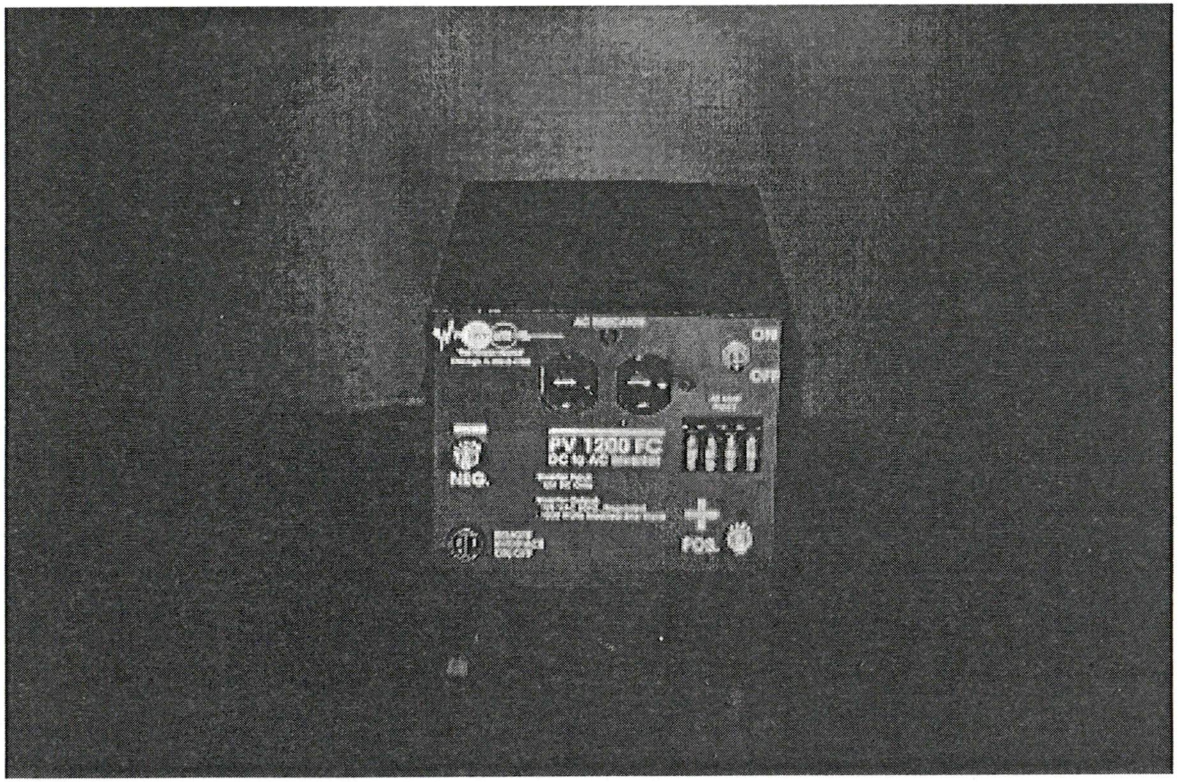

Figure 3.2. DC to AC power inverter used to supply 120V AC power to the GPR system.

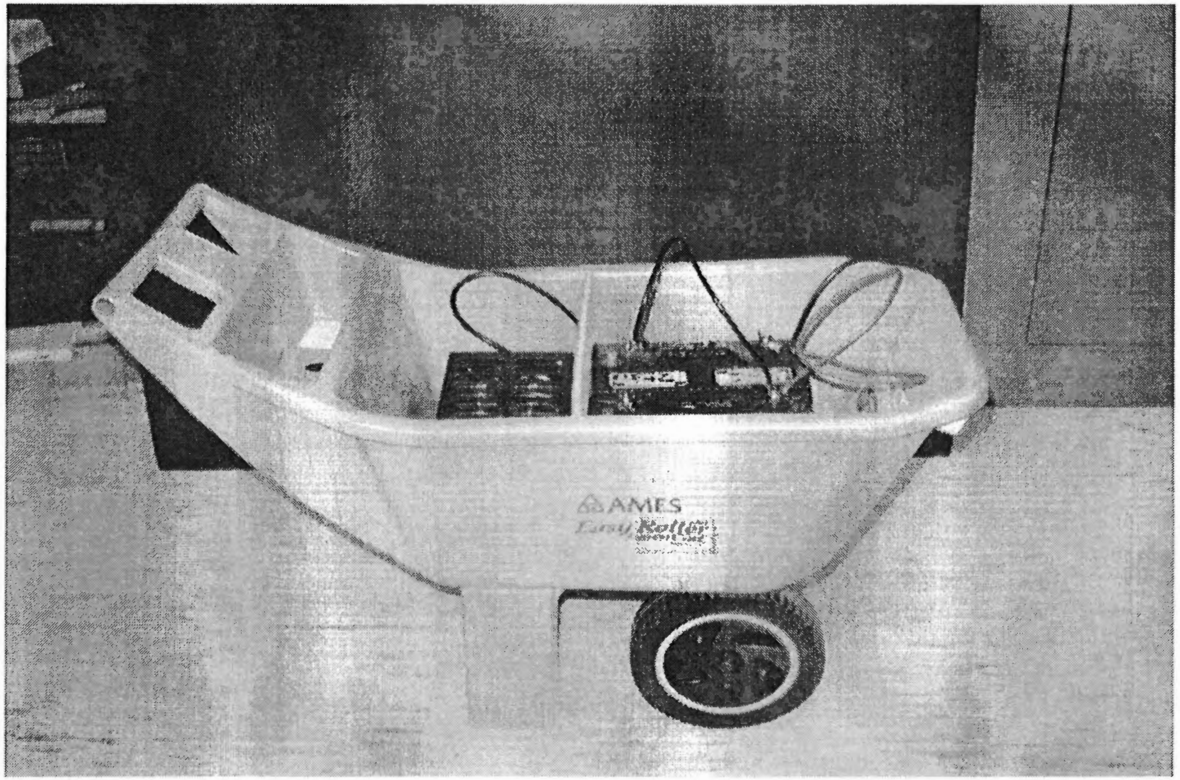

Figure 3.3. Batteries and power inverter used to power SIR System-10A.

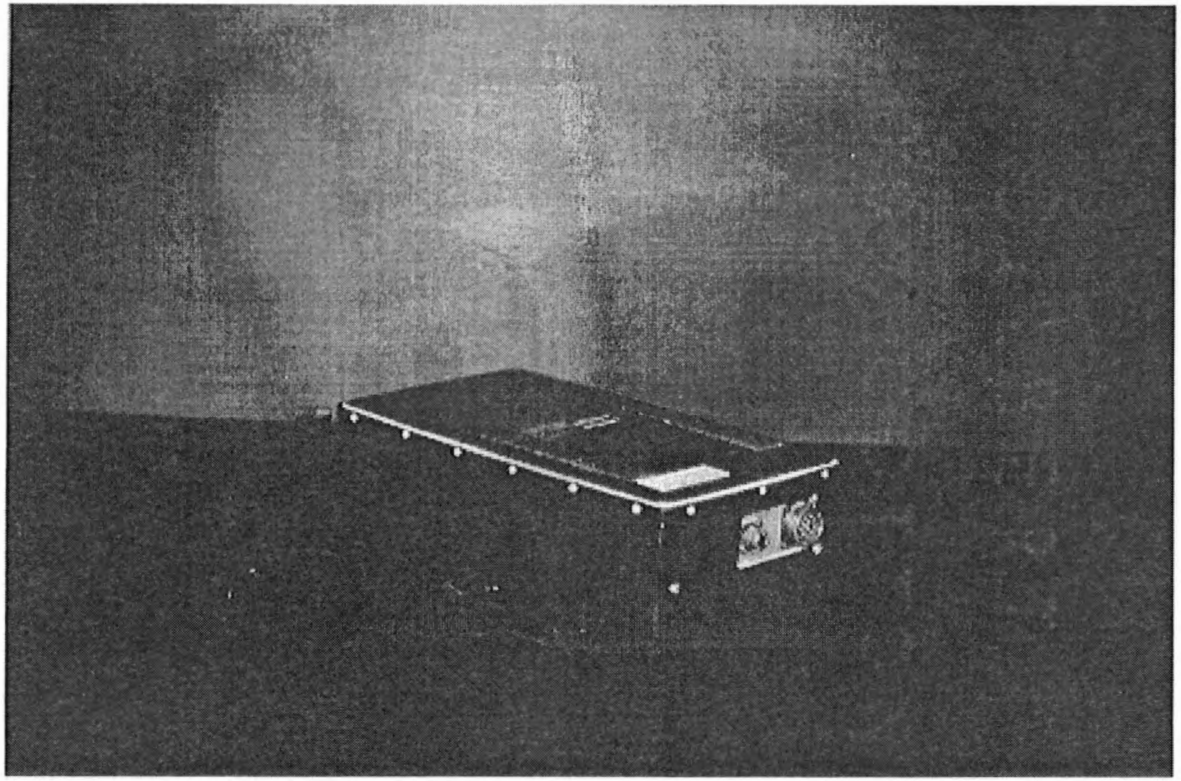

Figure 3.4. Nine hundred MHz antenna used in test one.

connectors for the control cable and hand marker. Data for this study were taken with two GSSI antennas: a 500 MHz and a 900 MHz.

For high-resolution shallow profiling, data were taken with a GSSI Model 3101D, 900-MHz antenna (Figure 3.4). Both the transmitter and receiver were enclosed in an 8 cm x 18 cm x 33 cm 2.3 kg plastic housing. With a pulse width of 1.1 ns, this antenna resolved narrow layers.

For deeper profiling, data were obtained using a GSSI Model 3102, 500-MHz antenna (Figure 3.5). This antenna was rented from J. D. Fett Co. (Houston, TX, USA). The transmitter and receiver were housed in a 13 cm x 39 cm x 42 cm fiberglass 7.7-kg container. With a 2-ns pulse width, this antenna was capable of greater penetration (but less resolution) than a 900-MHz antenna.

Miscellaneous Radar Equipment

For a small survey area (15-m radius or less), the radar system was operated from a stationary location. During this type of test, the antenna was manually towed. Larger surveys required more mobility. For the large surveys, a pickup truck or all-terrain vehicle (ATV) (Figure 3.6) transported the radar equipment, operator, and driver. ATV's provided adequate transport over rough terrain. To prevent interference caused by the metal ATV, the antenna was towed approximately 2 m behind the ATV.

Due to its small size, the antennas were flipped by surface irregularities and grass when towed. To prevent this, the antennas were mounted in a long plastic sled for mobile surveying. This smoothed the small surface irregularities and protected the antenna. The sled

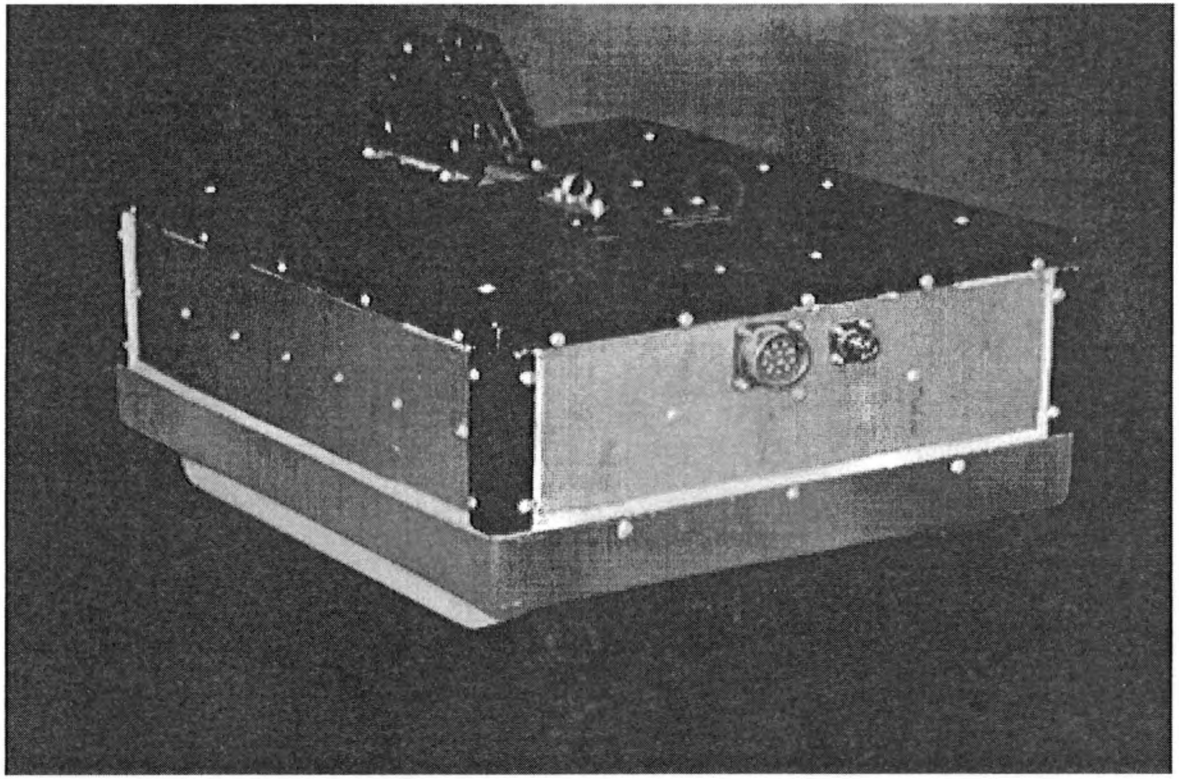

Figure 3.5. Five hundred MHz antenna used in test two and three.

Figure 3.6. ATV used to transport GPR equipment and tow antenna in test two.

also added weight to the antenna and prevented grass or other obstacles from lifting it off the surface.

Conventional Survey Equipment

Topographical data were taken with a Pentax Model PTS-10 total station (Figure 3.7). Depth to bedrock measurements were made with a 1.2-m long, 0.75-cm diameter metal rod with a removable 1.4-cm sharpened tip (Figure 3.8). For points with deeper soil, a 1.8-m long rod was used. Saturated soil was located by inserting an electronic device into the shallow wells (Figure 3.9). The device consisted of an open circuit attached to a buzzer. Upon contact with water, the circuit was completed, causing the buzzer to sound. When the buzzer sounded, a measuring stick attached to the sensor was read to find the depth to the water table.

Software

RADAN III was a general purpose signal processing package marketed by GSSI. An IBM PC/AT-386, 486, or compatible personal computer was required to run the software. With RADAN III, radar data from an SIR System-10A unit were displayed or printed in wiggle or line scan format. Annotations were added to the data within RADAN III and printed. Several processing functions were implemented to aid in interpretation of the data, including low and high pass filter, Deconvolution, Migration, Hilbert transform, arithmetic operations, range gain adjustments, and horizontal and surface normalization. RADAN III was also used to find the TT to subsurface interfaces and, if the σ was known, the depth.

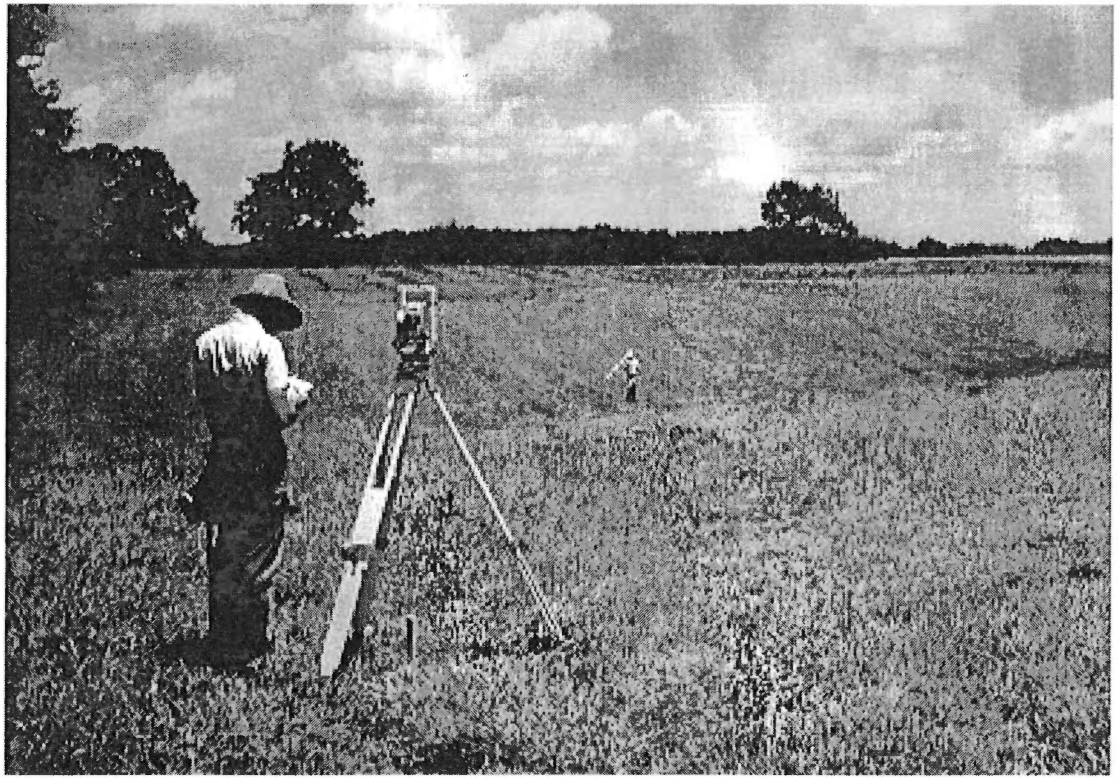

Figure 3.7. Pentax total station used to survey test sites.


Figure 3.8. Rock probe used to manually measure the depth to bedrock.

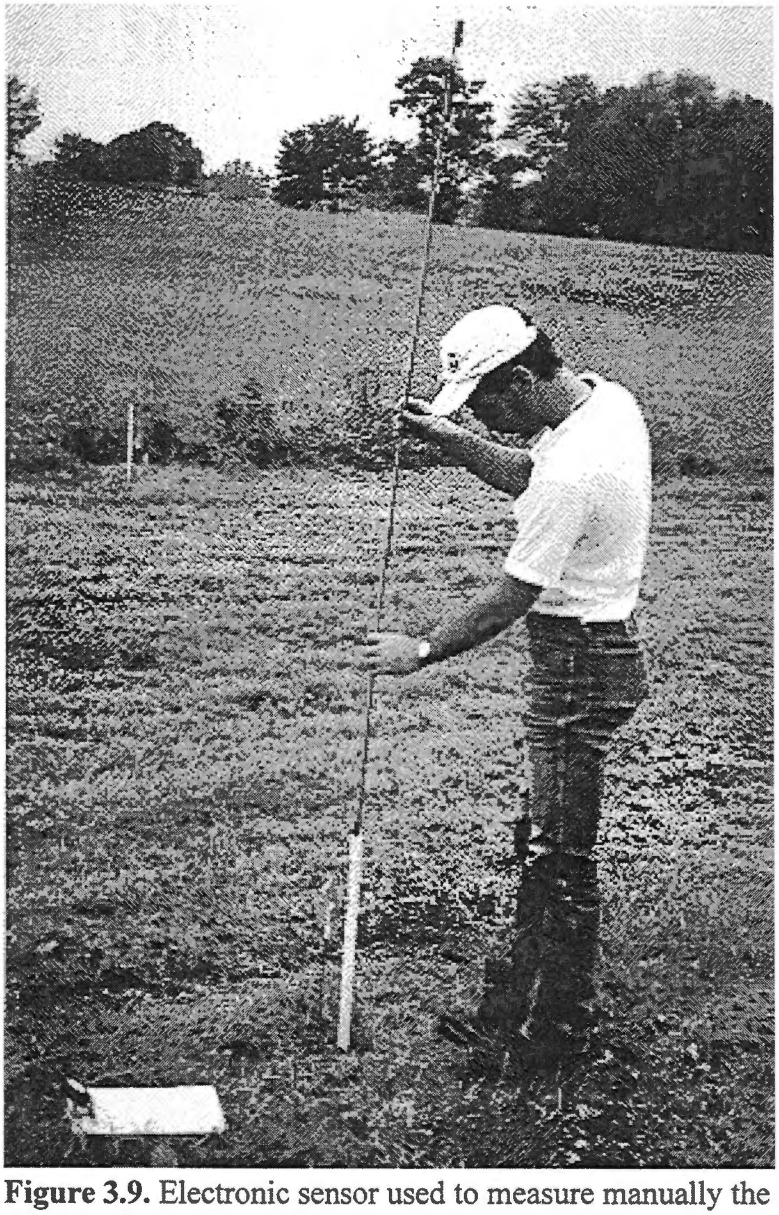

Figure 3.9. Electronic sensor used to measure manually the depth to the water table.

Surface and contour maps of the test sites were developed with Surfer™ for Windows, version 5.01 (Golden Software, Inc.). By interpolating irregularly spaced points into a regularly spaced grid, the software produced surface and contour maps. Annotations, boundary information, and drawings were added to maps created by the software. With the grid files created when the data were interpolated, volume, area, and planar area calculations were made. Surfer™ was used in these tests to develop surface, contour, and soil depth maps.

Adobe Photoshop™ for Windows, version 3.0, was used to import the radar data into a Windows format for printing. The software was primarily designed for photographers, but digitized radar images were handled in much the same way as a digitized photograph. Image enhancement, annotations, and printing through windows drivers were possible after importing the radar data into the Windows compatible software.

2. Conventional Survey

Three approximately ½-ha research sites were selected for detailed examination, based upon site recommendations by Carlie McCowan (Cumberland County NRCS Soil Survey Leader). The sites were part of a 20-ha remote research tract administered by The University of Tennessee Plateau Experiment Station (Figure 3.10). The research tract is beside the Clyde M. York 4-H Training Camp in Cumberland County, Tennessee, located approximately 3.5 km SW of the Crossville Airport.

All sites contained the sandy-loam soils of the Lily Series, which is a typical cropland soil series of the Cumberland Plateau. The shallow sites lie on upland sideslopes and

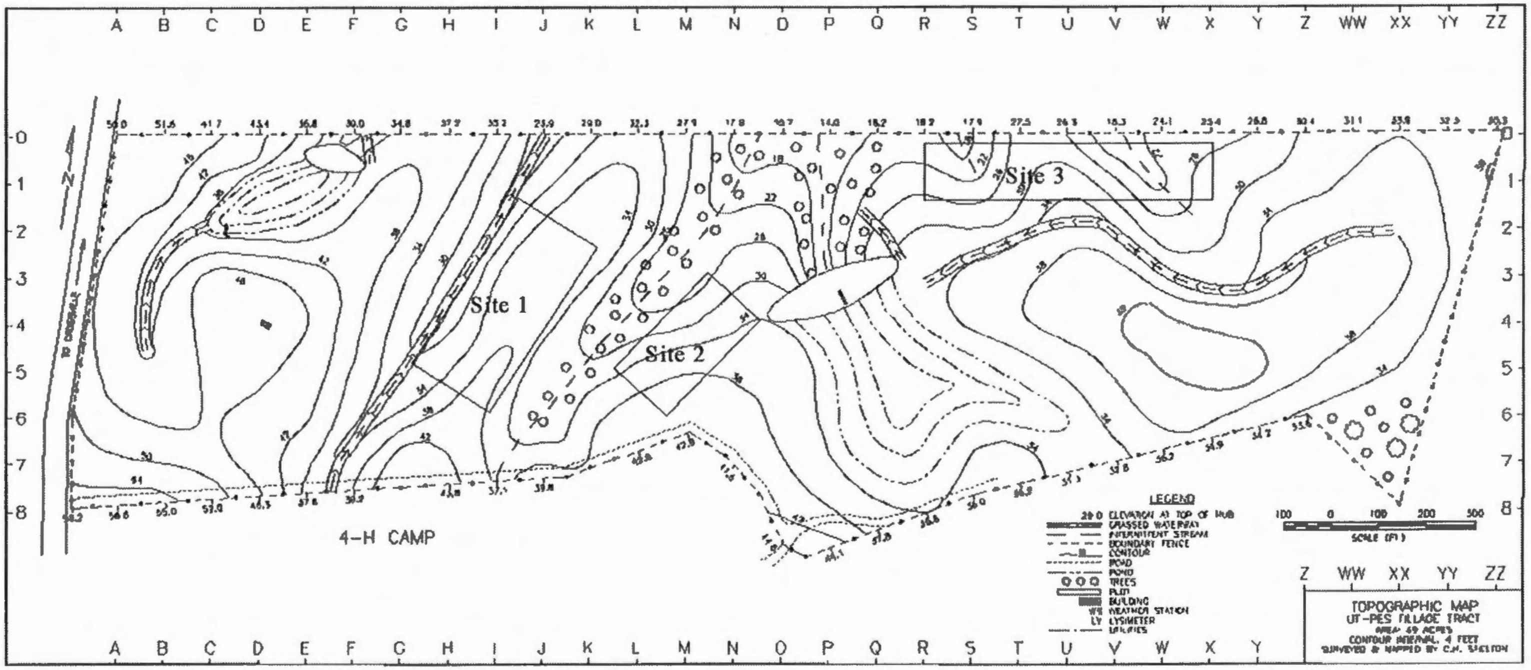

Figure 3.10. Research tract supervised by The University of Tennessee Pateau Experiment Station in which the GPR test sites were placed.

ridgetops with soil depths of approximately 1 m. Though the site has occasionally been tilled for row cropping during the last 50 years, it has been primarily maintained as pasture. This practice of alternating from pasture to cropland is common for the region.

Topographical survey data were gathered for each of the three sites, with the assistance of Joe Sarten (Experiment Station Engineer) operating the Pentax Model PTS-10 Total Station surveying instrument. The first site, identified as Site 1, was 75 m X 100 m with a small wet-weather stream along the western boundary (Figure 3.11). The next site, identified as Site 2, was 50 m X 75 m (Figure 3.12). The final site, identified as Site 3, was 170 m X 35 m (Figure 3.13). Elevation data were recorded on a grid approximately 10 m x 10 m. A numbered survey flag was placed at each surveyed point. Subsequently, manual depth-to-bedrock measurements were made at each flag location using a steel bedrock-probing rod. Topographical maps of the surface and bedrock were generated (Figures 3.11, 3.12, and 3.13) using the 3-D mapping software SURFER™. Using the surface and bedrock topographical profiles, soil depths were mapped.

A total of fifteen soil pits were excavated along the perimeter of the three sites. Each pit was named with a number letter combination. The number represented the site in which the pit was located, and the letter identified the pit (Figures 3.14., 3.15, and 3.16). The perimeter soil pits allowed more accurate descriptions of the soil horizons. Carlie McCowan, the NRCS Soil Survey Leader overseeing the mapping of soils in Cumberland County, provided a detailed soil description and horizon breaks for all pits (Appendix A).

The wet-weather watertable in Site 1 was monitored using 1.9 cm x 1.5 m schedule 40 PVC tubing, having numerous small holes drilled along the lower length. The tubes were

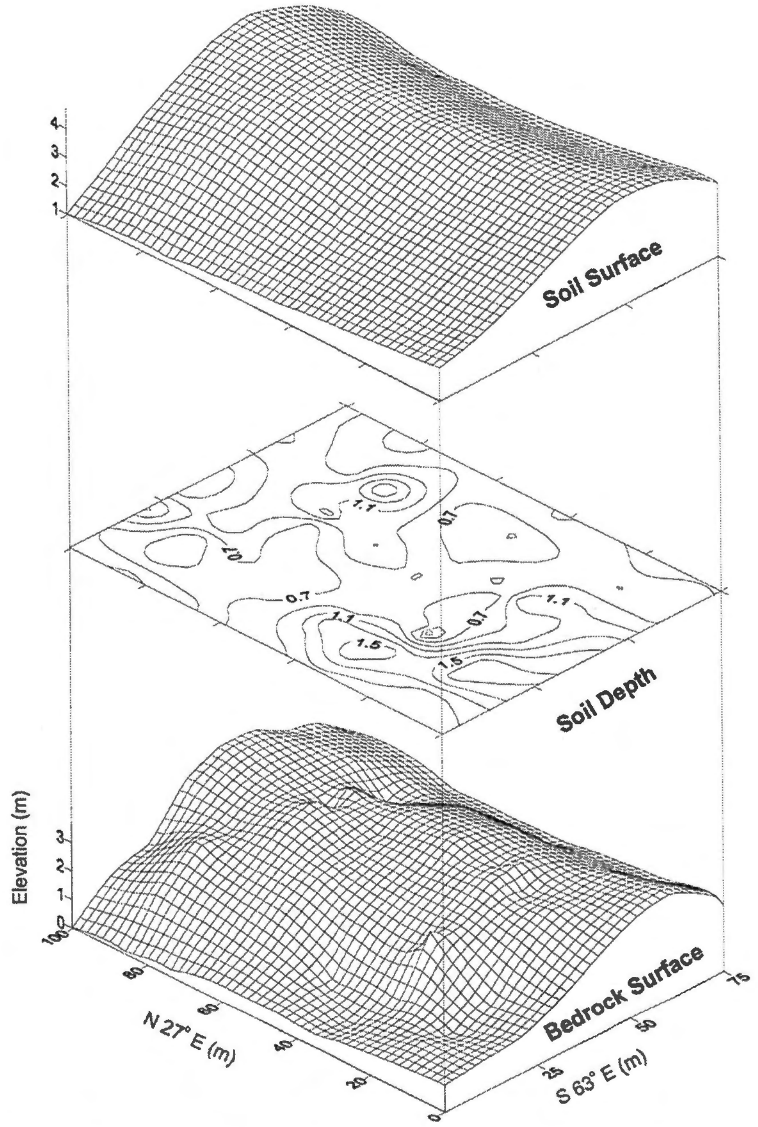

Figure 3.11. Surface, soil depth, and bedrock surface maps of Site 1. Based on data taken in conventional survey.

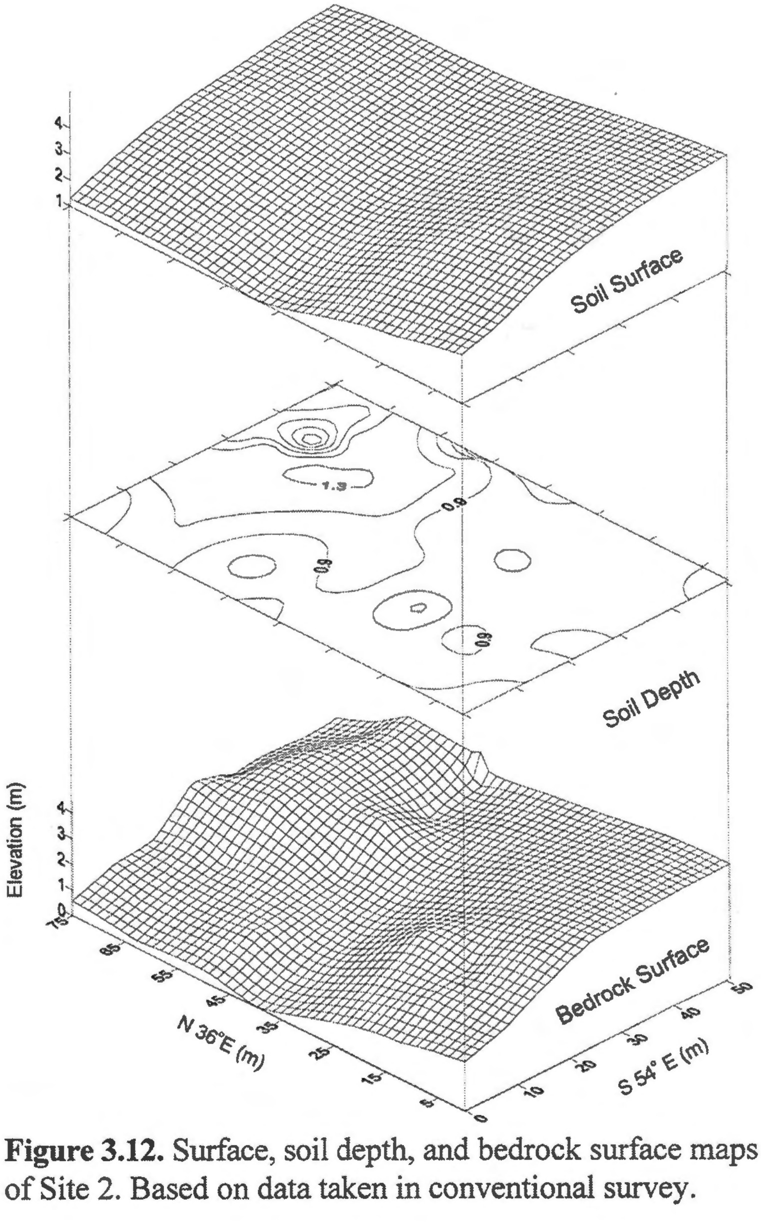

Figure 3.12. Surface, soil depth, and bedrock surface maps of Site 2. Based on data taken in conventional survey.

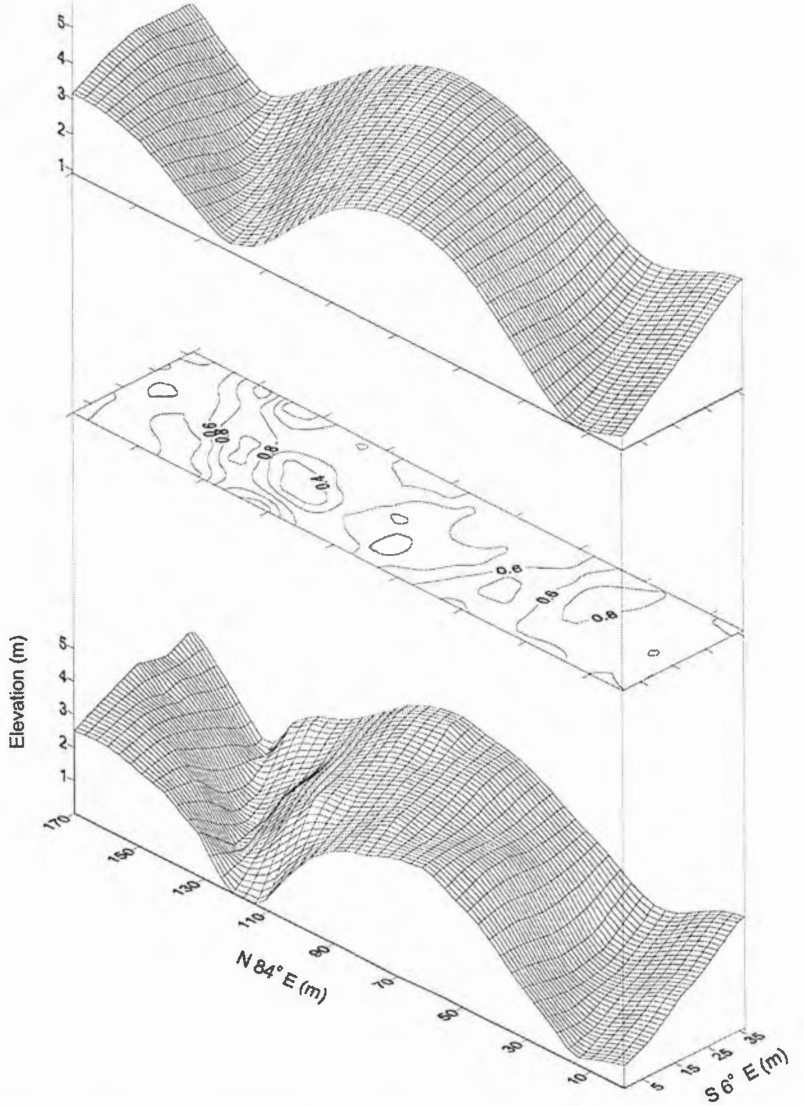

Figure 3.13. Surface, soil depth, and bedrock surface maps of Site 3. Based on data taken in conventional survey.

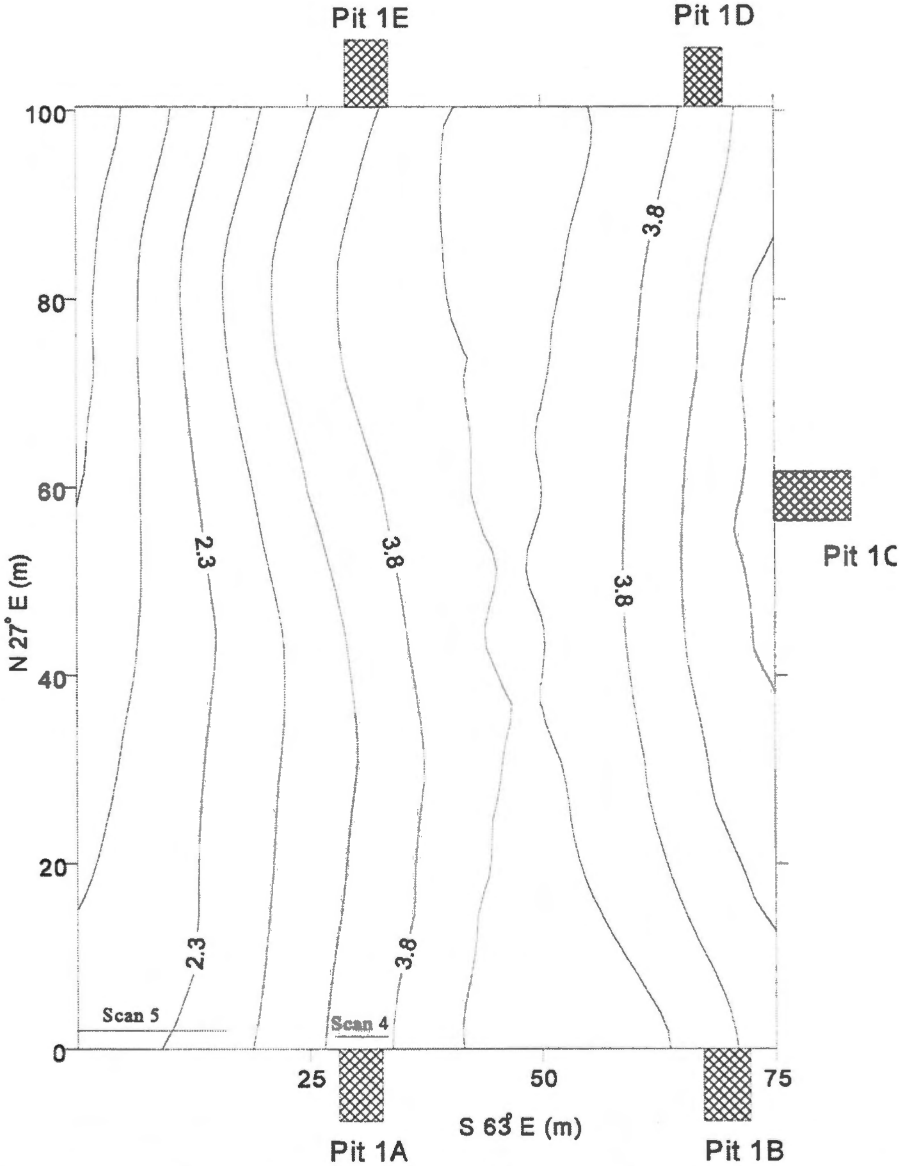

Figure 3.14. Contour map of Site 1 with soil pit location and names shown.

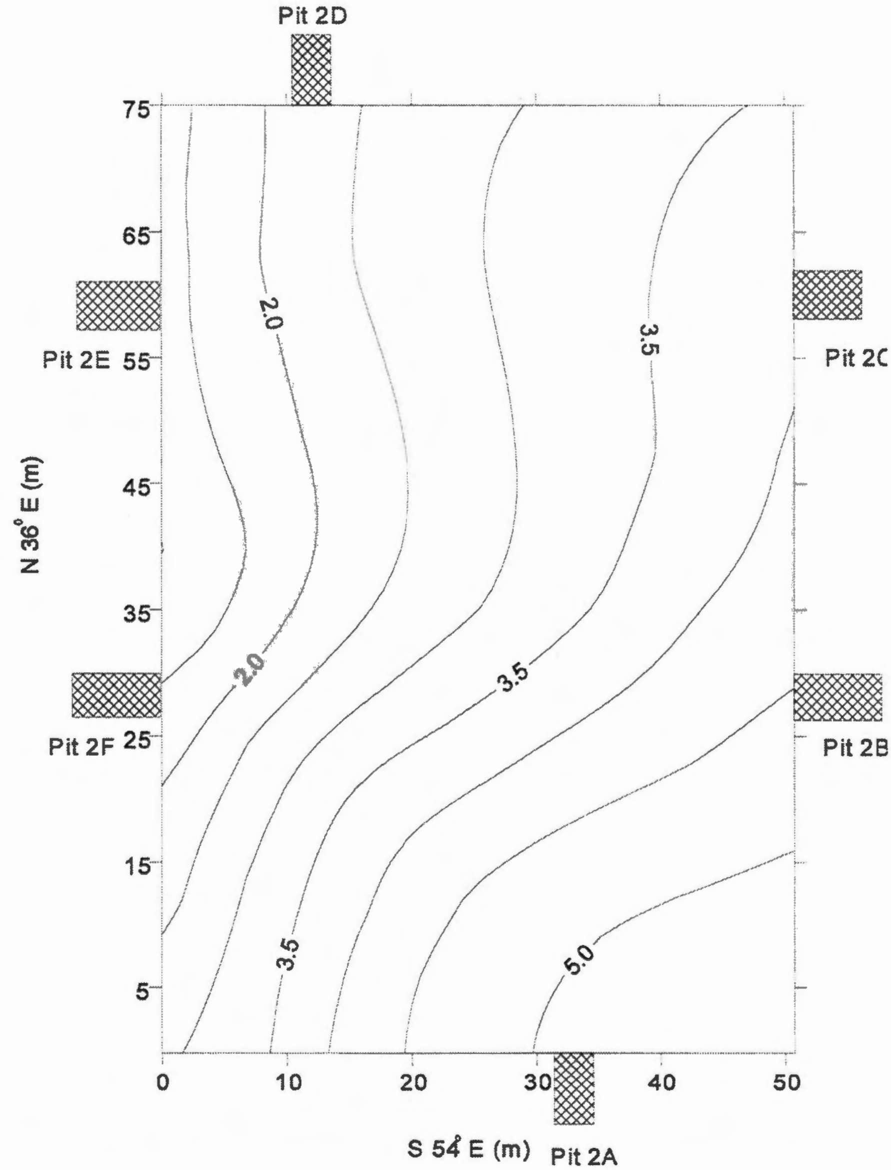

Figure 3.15. Contour map of Site 2 with soil pit locations and names shown.

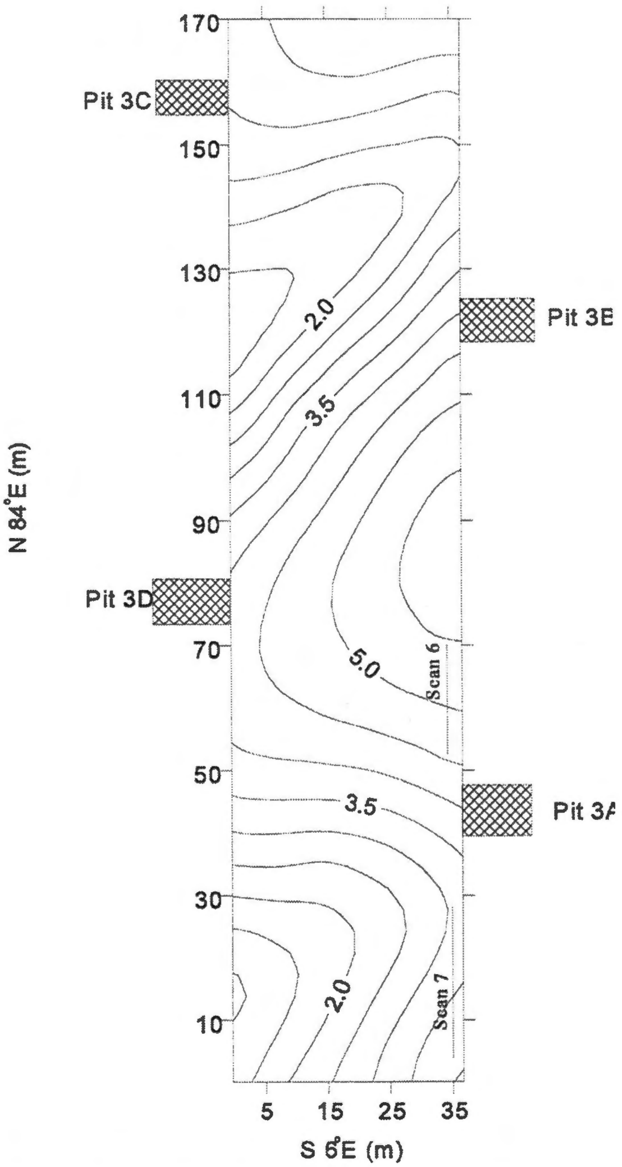

Figure 3.16. Contour map of Site 3 with soil pit locations and names shown.

dropped into bedrock-deep, 2-cm auger holes at each surveyed point where the wet-weather watertable was higher than the bedrock. These tubes remained in the ground. An electronic measuring ruler detected the depth-to-water level by emitting an audible signal upon contact with water as it was being lowered into the tube. The water table depth was plotted using the SURFER™ program (Figures 3.17).

3. Radar Survey

Test One

Data for the first test were taken on April 6, 1995, from a 15 m X 15 m site within Site 2. This small site, designated Site 2A, was located in the southwestern corner of Site 2 next to Pit 2A (Figure 3.18). Data were taken from a stationary location with the 900-MHz antenna.

Site 2A was selected for the first test for several reasons. First, the 900-MHz antenna is capable of penetrating about 1 m in the soils typical of the Cumberland Plateau. Selection of Site 2A was based on soil depths less than 1 m in Pit 2A and 2B (Appendix A). Second, a small site was desirable so that the detail of the survey could be increased. Increasing familiarity with the radar equipment was also a major goal of the first test. With a stationary test, more attention was given to the proper set up and calibration of the radar system.

By placing Site 2A next to Pit 2A, images in the radar data could be identified. Metal pipes inserted horizontally into the soil from within the pit provide identifiable marks in the radar data. Three pipes were placed in holes bored with a 5.5-cm hand auger. Each pipe was made of seamless steel tubing with an outside diameter of 4.8 cm and an inside diameter of

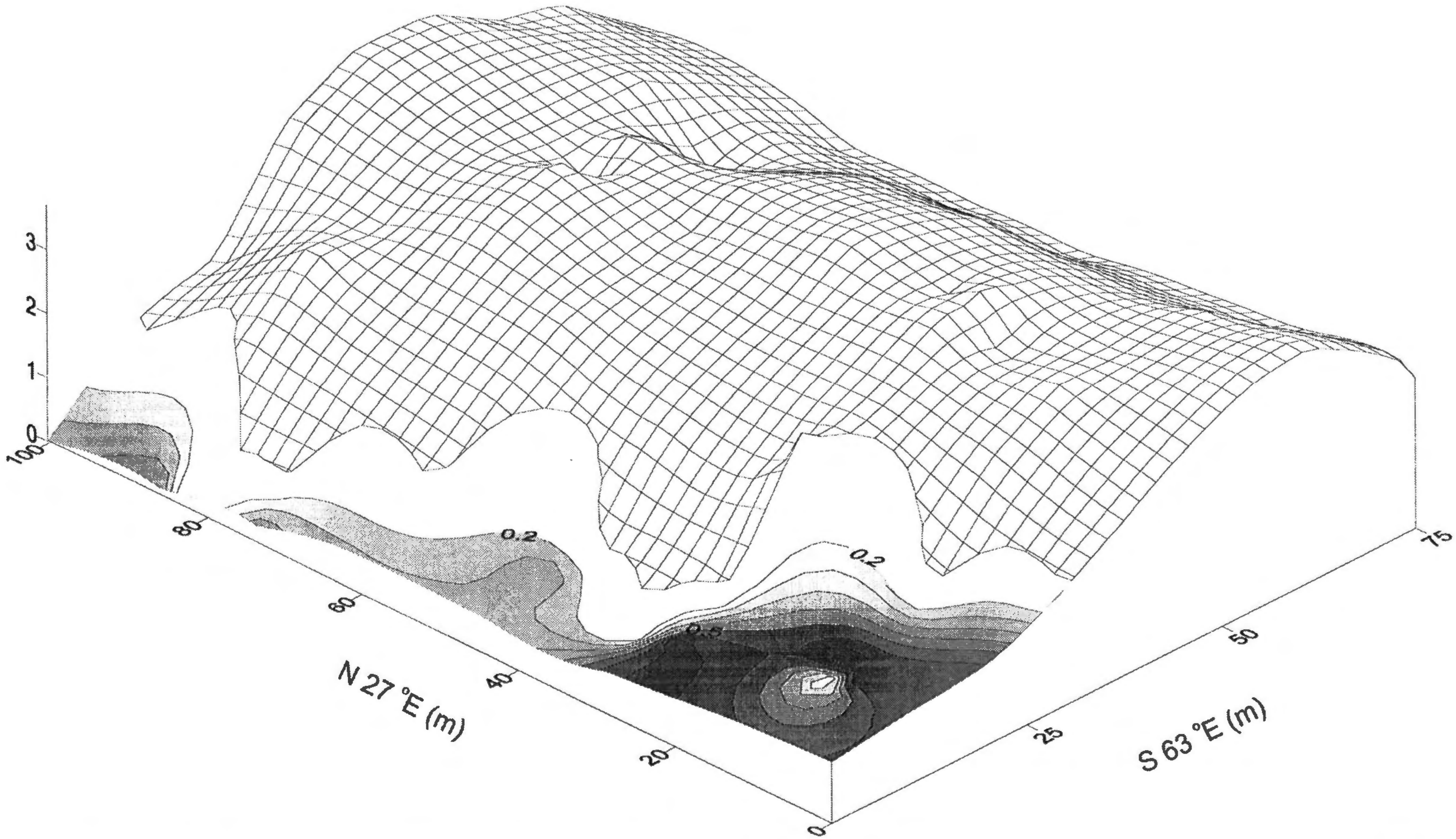

Figure 3.17. Bedrock surface map and contour map of Site 1 showing the physically measured distance from bedrock to the top of the saturated soil on August 14, 1995. Each contour line represents 0.1 m less water above bedrock.

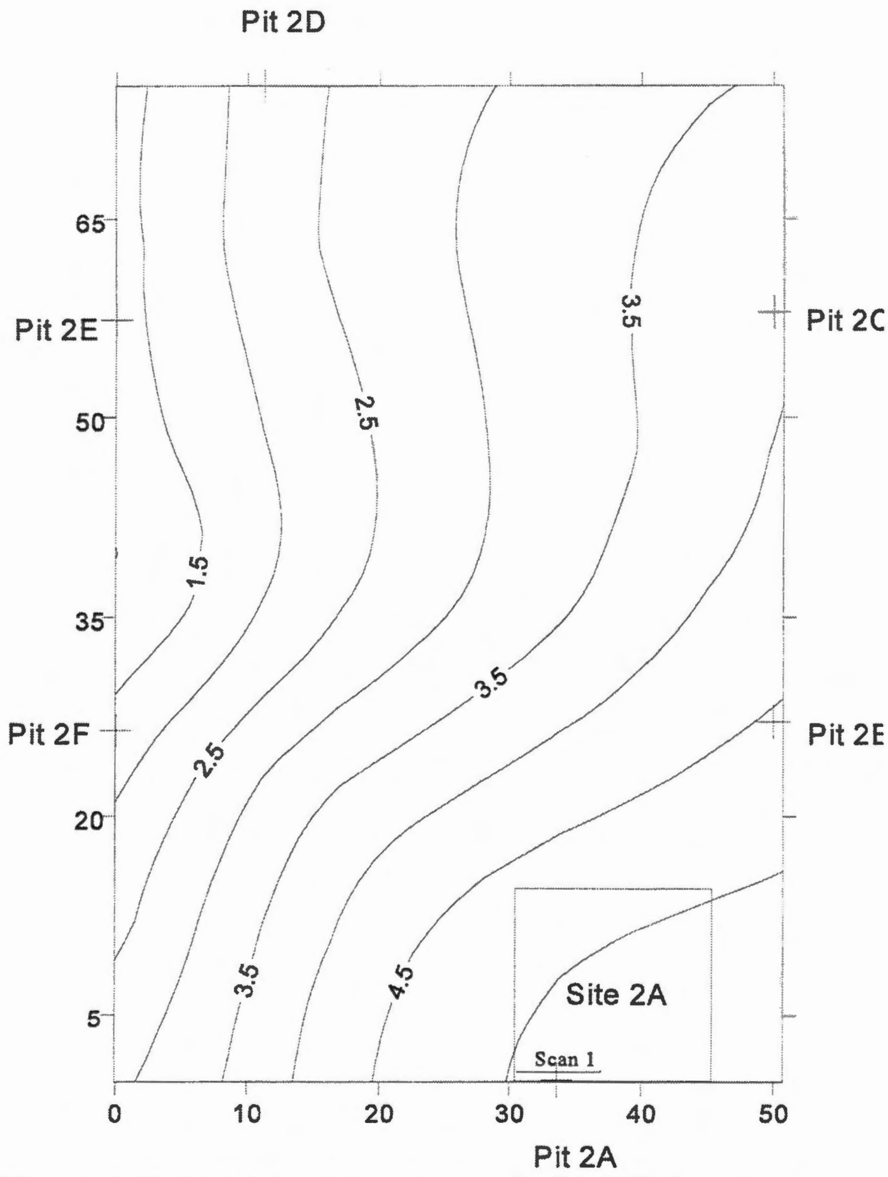

Figure 3.18. Location of Site 2A surved with GPR in test one.

4.1 cm. Pipe one was inserted at a depth of 20 cm near the top of the Bt horizon, the second at a depth of 51 cm within the BC horizon. The last pipe was inserted on top of the bedrock at a depth of 76.2 cm (Figure 3.19). Radar images taken near the pit could be compared with the actual soil profile. Soil features can then be identified by reflections in the radar data appearing at the same depth as the pipe in that interface.

Pit 2A was also used to develop a depth calibration for the radar data for the surrounding area. The TT of the radar wave to an object in the soil was stored in the radar data. One way to convert this time into depth was to calculate the σ of the soil. By pulling an antenna over the metal pipes buried within the soil, the TT of the radar wave to and from the pipe was found. With the known depth of the metal pipes and the TT of the radar wave, the σ can be found. With the σ, depth can be calculated from the radar data for the surrounding similar soils under similar moisture conditions. Changes in soil type or moisture conditions would change the σ, and a new calibration would be required.

Site 2A was split into 16 transects spaced 1 m apart. To lay out the transects, survey flags were placed 1 m apart along the east and west sides of Site 2A. Nylon string was then stretched between the two flags that were opposite each other. Each string was then assigned a letter for identification, with string A being near Pit 2A and P being farthest from the pit. Radar scans were then taken along each side of each string. Each scan was named by the letter of the two strings it was between, with the nearest string the first letter. For example, a scan to the left of line B was called scan BA. Scans were taken parallel to Pit 2A in a westerly direction (Figure 3.20). Marks were placed in the data manually every 3.75 m to

Figure 3.19. Metal rods inserted into the soil profile for calibrating the GPR data and identifying soil features.

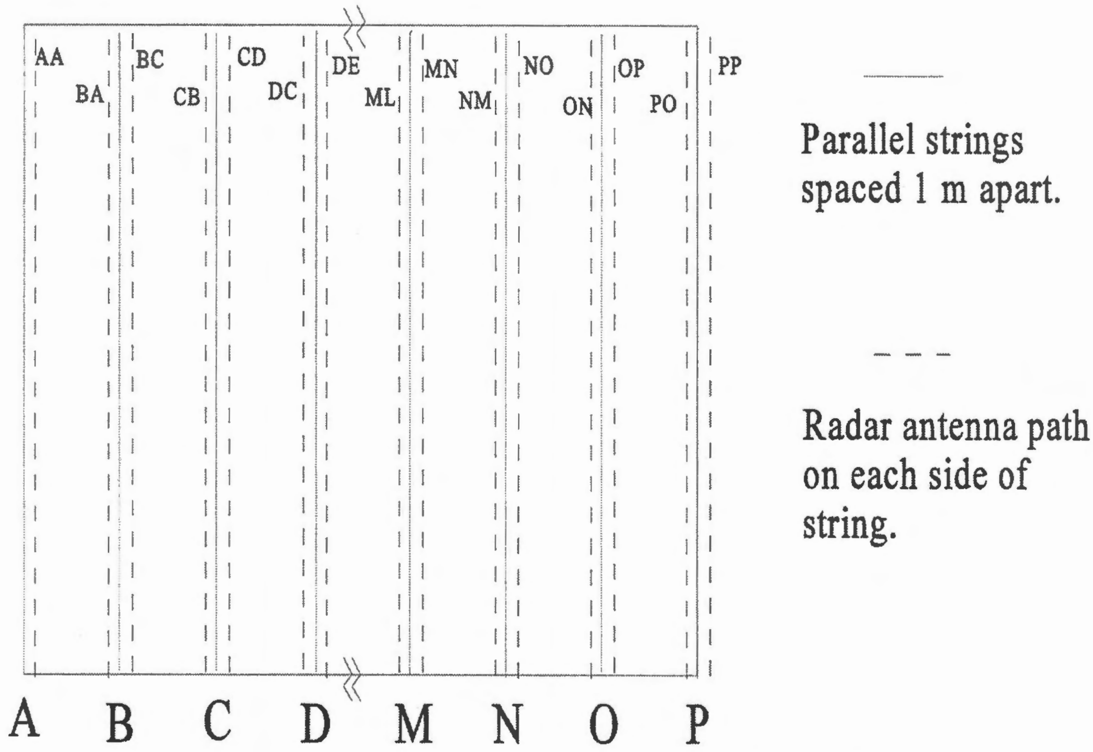

Figure 3.20. Spacing and nomenclature of radar transects taken in Plot 2A during test one.

provide a horizontal reference in the data. Operator adjustable GPR system settings are shown in Table 3.1.

Test Two

Test two was conducted on July 10, 1995 with a 500-MHz antenna. Data were taken from each of the three test sites for this test. Four evenly spaced transects were made down the length of each of the sites. Sites 1 and 2 were scanned from south to north. Site 3 was scanned from west to east. Due to the size of the sites, all surveys were conducted from an ATV. Pit 2A was again used to develop a depth calibration for the test. GPR settings for test two are shown in Table 3.1.

Test Three

On August 14, 1995, a 500-MHz antenna was used to survey the southern end of Site 1. Each scan began in the southeastern corner, in the stream, and was pulled up the hill to the southwestern corner. The radar unit was operated from the rear of a covered pickup truck. Survey flags were placed 5 m apart along the 75-m transect. While pulling the antenna by hand, the radar operator placed physical marks in the radar data at each flag. This provided points of known location in the radar data. GPR settings for test three are shown in Table 3.1.

To make accurate depth predictions from the radar data near the stream, the σ of that soil had to be determined. To accomplish this, a metal pipe similar to that used in test one was inserted horizontally into the soil at a depth of 0.762 m. Radar scans taken over the pipe

Table 3.1. GPR system settings for three tests on the Cumberland Plateau.

Setting	Test #1	Test #2	Test #3
Antenna			
Model	3101D	3102	3102
Rated Frequency (MHz)	900	500	500
Pulse Width (ns)	1.1	2	2
Range (ns)	30	60	60
Scans per Second	49.984	49.984	49.984
Samples per Scan	256	512	512
IIR High Pass Filter			
Poles	2	2	2
Frequency	4	5	5
IIR Low Pass Filter			
Poles	2	2	2
Frequency	54	55	60
Horizontal Low Pass Filter	3	5	5

provided the TT of the radar wave to the pipe. Using equation 1.1 the σ of the soil was found.

To find the interface caused by the saturated soil on the radar data, the level of saturated soil at the time of the scans must be known. With the electronic measuring device, the water level was recorded at each of the shallow wells following the radar scans. Using SURFER™ topographical maps of the level of saturated soil were created (Figure 3.21). With the known depth of the water table, the reflection in the radar data caused by the saturated soil was identified.

Horizontal References

Linking the data taken during GPR surveys to known locations in the field was a difficult time-consuming task. In the first test, the site was small enough to allow strings to be stretched the length of each transect. By placing markers at 5-m intervals along the strings, marks could be accurately placed in the GPR data. Survey flags were placed at 5-m intervals along the single 75-m transect in test three. By manually placing a mark in the radar data as the antenna passed the flag, the data were connected to a known location in the site. These methods of tying the radar data to actual locations were effective in small sites. During test two, the survey area was too large to place markers for a horizontal reference. Soil pits and natural landmarks were used as horizontal reference points during this test.

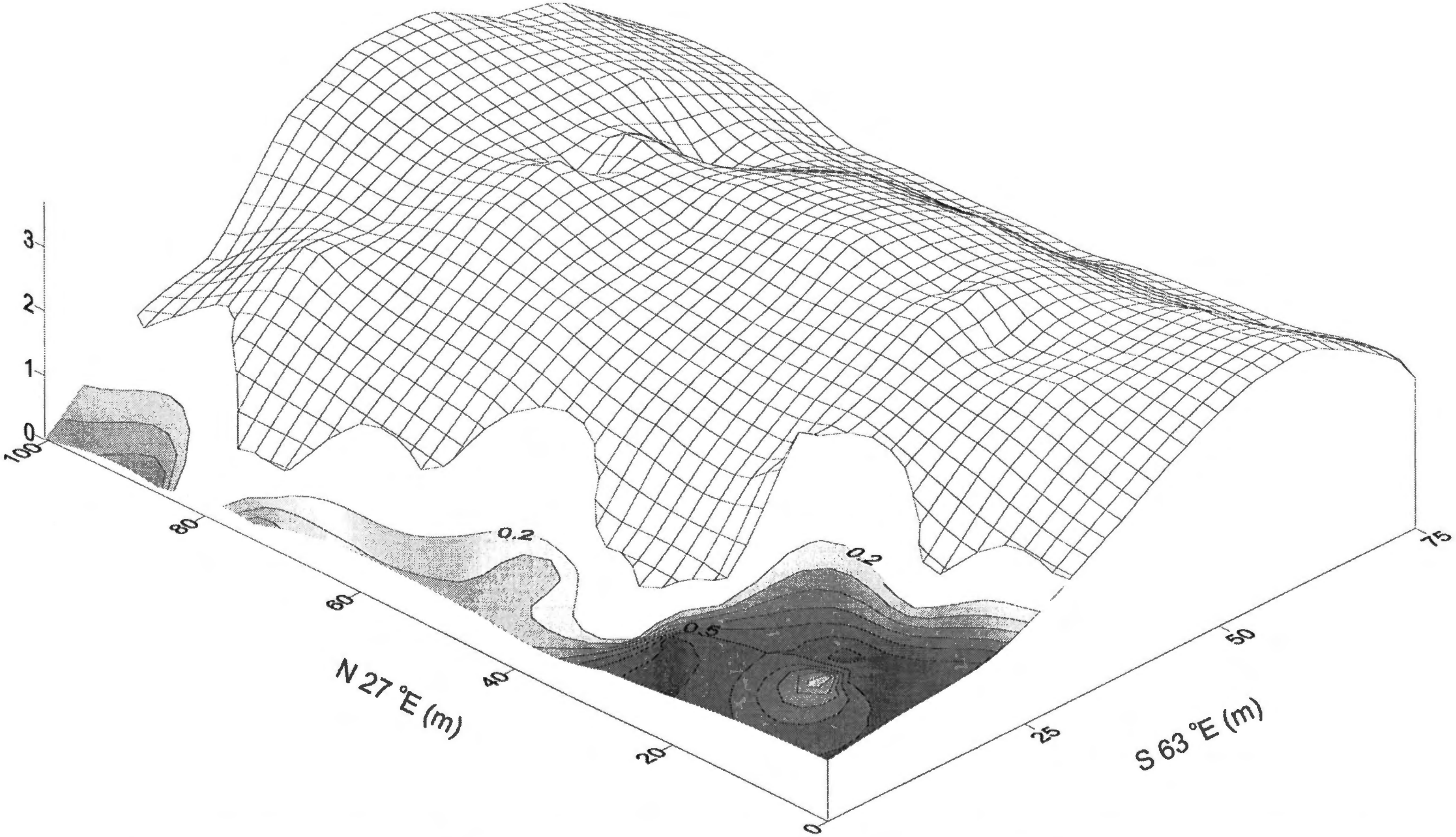

Figure 3.21. Bedrock surface map and contour map of Site 1 showing the physically measured distance from bedrock to the top of the saturated soil on August 14, 1995. Each contour line represents 0.1 m less water above bedrock.

Chapter 4

Results and Discussion

1. GPR Survey

Image Interpretation

Subsurface data in this study was taken in the linescan mode and displayed in a greyscale format. The data can be displayed using a variety of color scales or in the wiggle format. As shown in Figure 1.5, shades of grey near black or white represented strong radar reflections. Shades of grey near the center of the scale represented weak or no reflections. The strength of the reflections indicated the degree of change or the abruptness of the change of the σ in the soil. Since some soil features did not have drastically different σ than the surrounding soil, strong reflections were not the only indicator of major soil features. As experience with radar was gained in the soils of the test sites, the strength of the reflection served as a method for preliminary identification of subsurface interfaces.

Positive identification of subsurface soil features was only made by comparing ground truth data to radar data. This method of image identification worked best when the feature of interest changed in depth. By comparing the change in depth of an image in calibrated radar data to the actual physically measured change in depth, subsurface features were identified. Identification of subsurface features that remain at the same depth for great distances were much more difficult to identify. By placing metal pipes horizontally in the soil at the depth of the interface of interest, an identifiable mark was placed in the radar data. Radar reflections from the soil interface were then identified.

GPR images of subsurface interfaces were verified with a three step process. First, the interpretation of the data must obey the laws of physics. For example, the σ used to convert TT into depth must be reasonable. Tables such as table 1.1 have been published listing the approximate σ of many substances. If unreasonable σ values must be inserted for the GPR data to match the physical measurements then the GPR data was improperly interpreted. The next step in verifying GPR data was made by allowing specialists (soil scientists, geologists, hydrogeologists) who were very familiar with the geographical area being surveyed to examine the data. This method was especially useful until the radar operators became familiar with the subsurface characteristics of the area. Finally, comparison of the measurements interpreted from GPR data to actual ground truth measurements was used to verify the findings of the radar survey. Smith et al. (1992) suggest that three ground truth measurements provides the optimum number of physical measurements to calibrate and verify GPR data.

Test One

Calibration. Calibration of the radar system provided a method of converting the TT of the radar data into depth. In test one, the radar system was calibrated by towing the 900-MHz antenna over the pipes inserted in the side of Pit 2A. Hyperbolic shaped reflections of the pipes provided identifiable images in the radar data (Figure 4.1). Using equation 1.1, the σ of the soil from the surface to the depth of each pipe was calculated. Pipe depth, TT of the

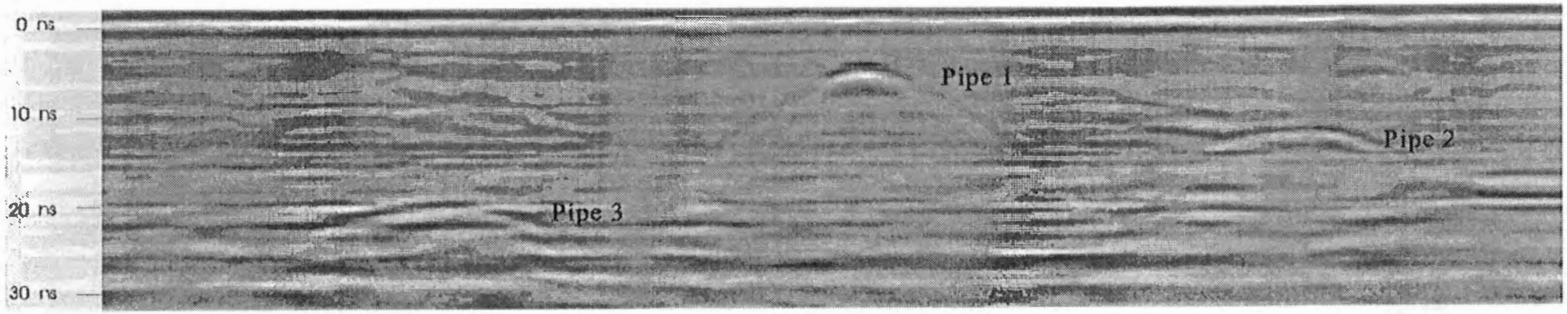

Figure 4.1. Hyperbolic images of metal pipes inserted horizontally from within Pit 2A. Data taken with a 900-MHz antenna. The location of this 7-m scan, labeled scan 1, is shown in Figure 3.18.

radar wave to the pipe, and the σ of the soil are shown in Table 4.1.

As shown in Table 4.1, the σ of the soil is different at each of the soil depths. Since the σ of the soil changes with increasing depth, the propagation speed of the radar wave also changes. To compensate for the change in travel speed of the radar wave, depth predictions made from GPR data were based on σ calculated at near the same depth as the interface of interest.

Horizon Identification. In Pit 2A, pipes were placed near the Ap/Bt horizon break, within the BC horizon, and just above bedrock. The pipes were used for identification of soil horizons. Hyperbolic images of the pipes provided landmarks at known horizon breaks in the radar data. Reflections in the data that appeared near the pipes were identified and tracked throughout the site.

The first pipe was placed 20 cm from the surface. The shallow pipe was easily found in the radar data. Naturally occurring reflections were recorded in the data at around 4.22 ns and at 7.03 ns (Figure 4.2). By inserting the σ and the TT to the interfaces into equation 1.1, the depths of the reflections were found to be 17 cm and 28 cm. The break between the Ap and Bt horizon, as determined by soil scientists in the field, was 13 cm below the surface. The second deepest pipe, 51 cm from the surface, placed within the BC horizon was also easily seen. A reflection was observed just below pipe two at 15.47 ns (Figure 4.3). With the σ based on the top 51 cm of soil, the depth to this reflection was 65 cm. This reflection occurred near the BC - Cr horizon break, which was 64 cm from the surface.

The third pipe was placed just above the bedrock (76 cm from the surface). This pipe

Table 4.1. Depth, and TT to each pipe in Pit 2A and the σ of each section of soil from the surface to each pipe on April 6, 1995.

Pipe	Depth (cm)	TT (ns)	σ
1	20	5.04	14.15
2	50.8	11.95	12.70
3	76.2	17.70	12.38

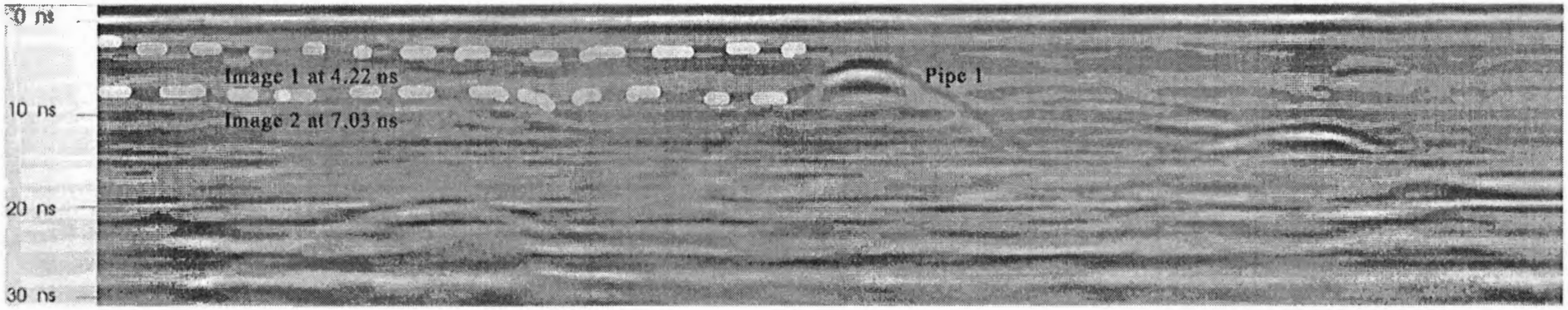

Figure 4.2. Reflections at approximately the depth of the argillic horizon are shown in this image taken with a 900-MHz antenna in test one. The two reflections are highlighted with a dashed line on the left side of the image. The location of this 7-m scan, labeled scan 1, is shown in Figure 3.18.

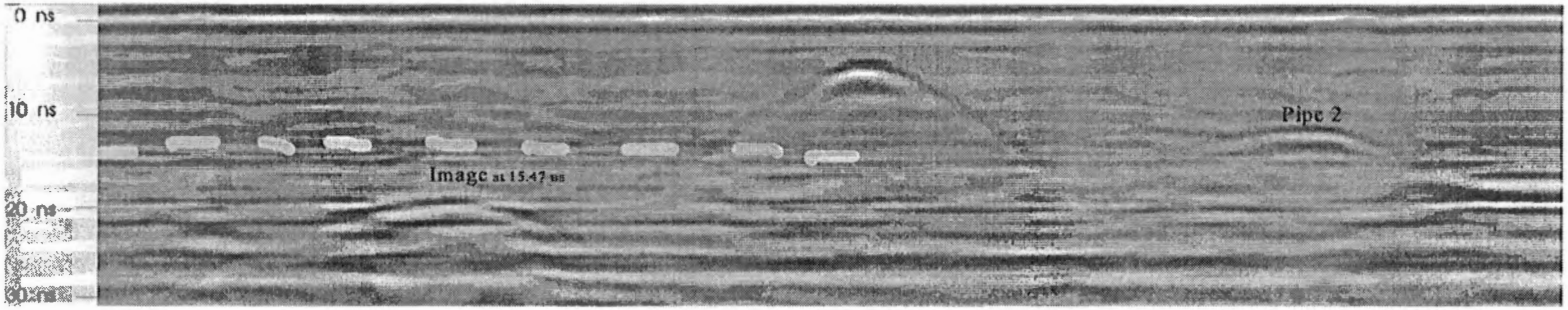

Figure 4.3. Radar reflections at approximately the BC\Cr interface are shown in the image taken with a 900-MHz antenna in test one. The reflection is highlighted with a dashed line on the left side of the image. The location of this 7-m scan, labeled scan 1, is shown in Figure 3.18.

was more difficult to locate than the previous two. Difficulty in finding the deepest pipe could be due to the depth of the pipe, the penetration limitations of the antenna, or the size of the pipe. Pipe three and the bedrock were near the depth limits of the 900-MHz antenna. Weak reflections were apparent at 19.34 ns (Figure 4.4). Based on the σ calculated from the TT to the third pipe, the depth of this reflection was found to be 82 cm. This depth closely matched the bedrock depth of 76 cm. After images in the data were identified, they were tracked throughout the site.

Even though reflections were recorded near the horizon breaks in the site, positive identification of the horizons was made difficult by two factors. First, soil depth and depth to the horizons were consistent throughout the small site. Second, noise and false reflections are common in most radar systems. Reflections from power lines, trees, vehicles, or people are common causes of system noise. Noise is also caused by reverbations of the radar signal in the antenna or control cable. Distinguishing between the interfaces that occurred at the same depth throughout the site and the system noise was difficult.

Identification of soil characteristics from inserted metal pipes was made difficult by several other factors. The soil survey was based on one particular soil profile on the edge of Pit 2A. The radar profile that was compared to this soil survey was taken within the site about 0.5 m from the pit. Radar images were also formed from the average of the returning signals from the cone of radar energy that was emitted by the antenna. Horizon development on the Cumberland Plateau was weak, and changes from one horizon to another are gradual. Horizon breaks made in the field by professional soil scientists were based on guidelines set by the Soil Survey Staff (1992). Even with the standardized method of soil classification,

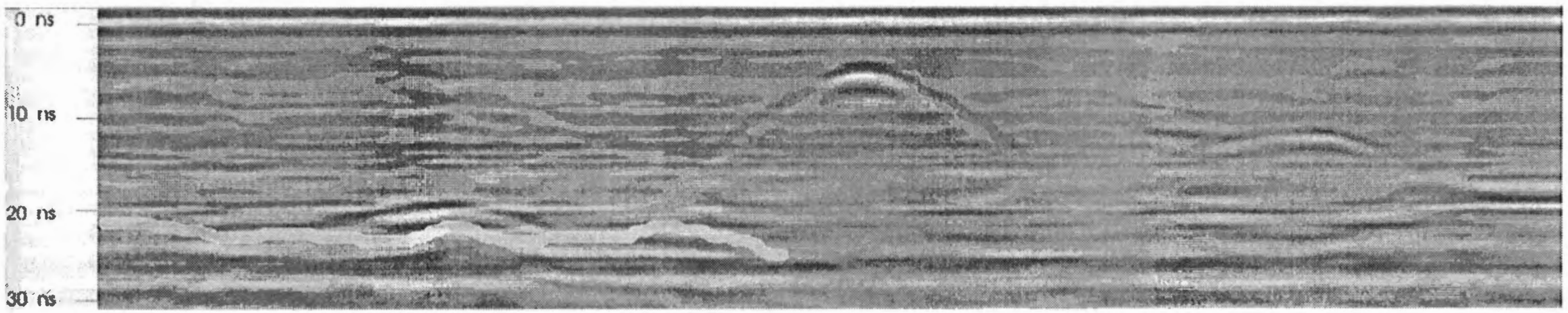

Figure 4.4. Radar reflections at approximately the depth of the bedrock taken with a 900-MHz antenna in test one. The reflection is highlighted with a solid line on the left side of the image. The location of this 7-m scan, labeled scan 1, is shown in Figure 3.18.

soil scientists often disagree slightly on the exact location of horizon breaks. GPR images were based solely on electrical interfaces. Many interfaces in the soil strong enough to cause a radar reflection did not occur at exactly the same point that was picked by a soil scientist.

Test Two

Calibration. The radar system was once again calibrated by pulling the 500-MHz antenna over the pipes inserted in Pit 2A (Figure 4.5). Since the σ of the soil was affected by the moisture content and moisture content was affected by weather, calibration was required before each test. Equation 1.1 was once again used to calculate the σ for each section of soil. Pipe depth, TT of the radar wave, and the σ of the soil in Pit 2A on July 10, 1995, are shown in Table 4.2. With the σ, depth to objects in the radar data were found as long as the soil type remained similar.

Horizon Identification. The bedrock was identified with more confidence in test two by scanning over the pipes in Pit 2A and taking longer scans in the survey. Scans were taken from the lengths of each of the test sites. The metal pipes were used to find the general depth at which the bedrock occurred. The antenna was then towed to an area where the soil depth changed. The TT to true reflections in the radar data changed as the depth to the interface changed. System noise remained constant throughout the scan.

The most dramatic change occurred between Pit 2B and Pit 2C in Site 2. Between the two pits, the parent material changed from sandstone bedrock to mudstone. Figure 4.6 shows radar profiles taken between the two pits. At Pit 2B, the sandstone bedrock produced

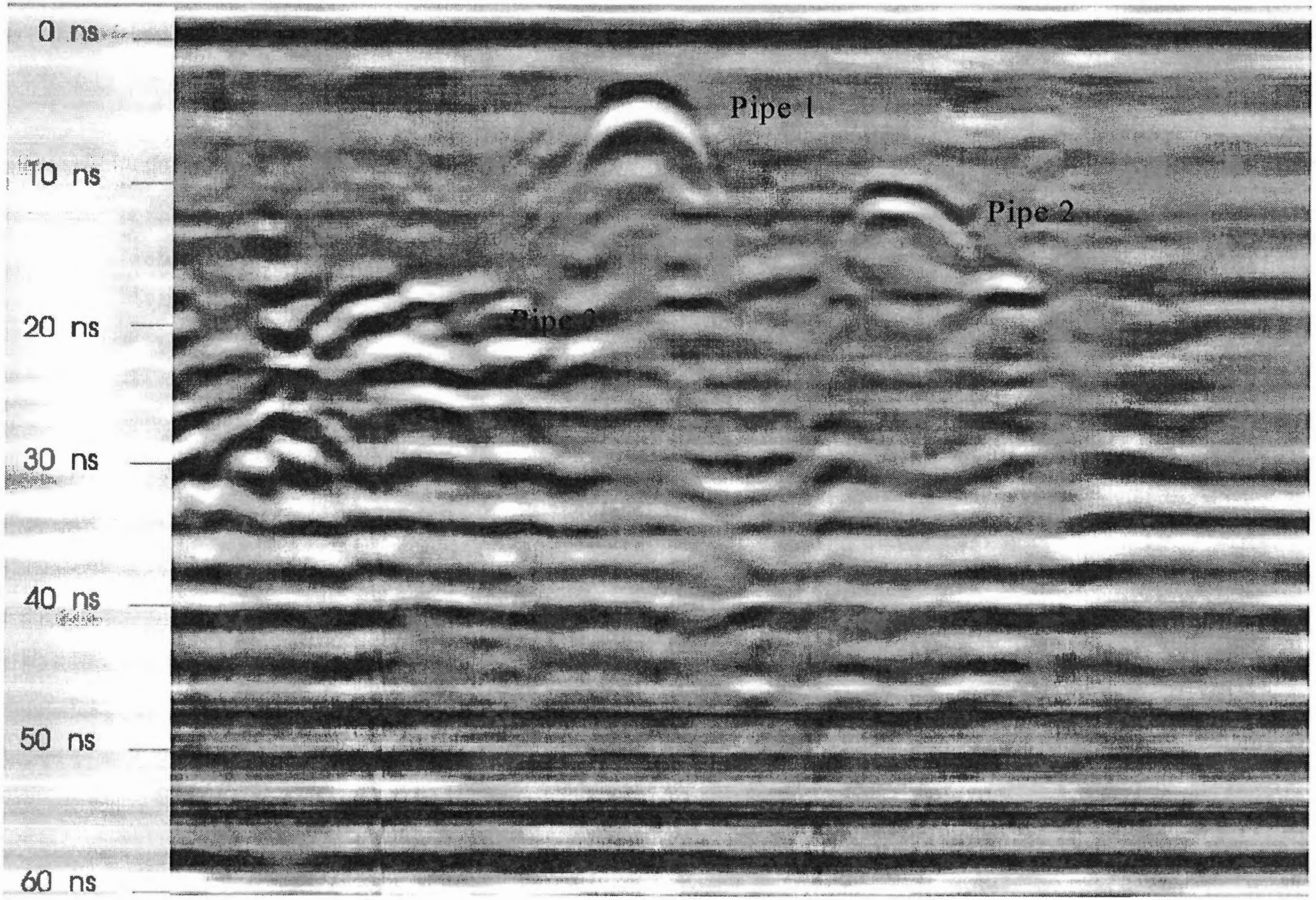

Figure 4.5. Hyperbolic images of metal pipes inserted horizontally from within Pit 2A. Data taken with a 500-MHz antenna. The location of this 5.5-m scan, labeled scan 1, is shown in Figure 3.18.

Table 4.2. Depth, and TT to each pipe in Pit 2A and the σ of each section of soil from the surface to each pipe on July 10, 1995.

Pipe	Depth (cm)	TT (ns)	σ
1	20	4.8	12.85
2	50.8	11.48	11.72
3	76.2	17.58	12.22

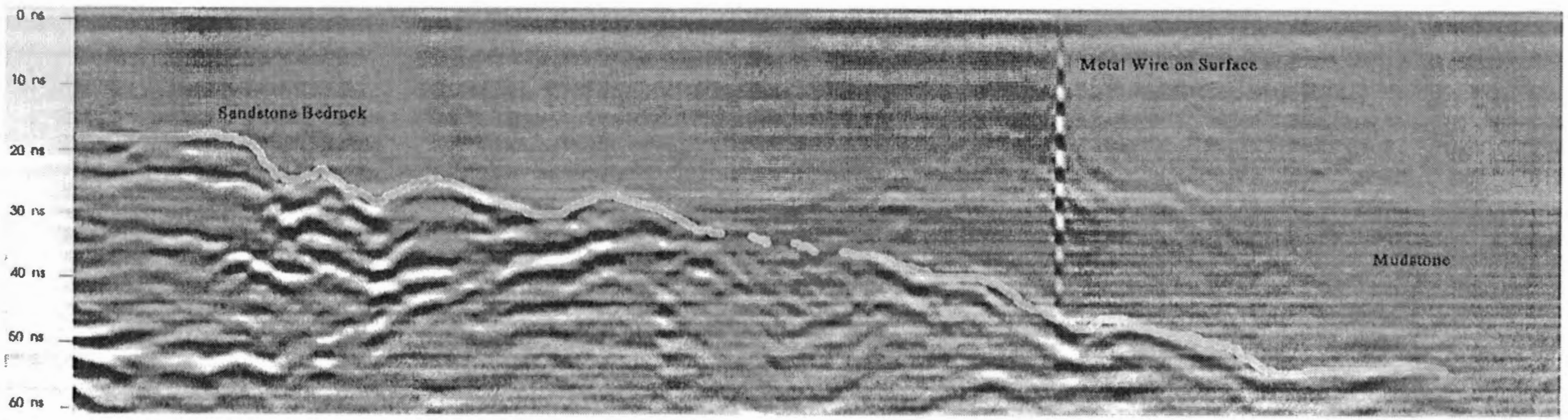

Figure 4.6. Radar data collected between Pit 2B and 2C showing sandstone bedrock (left) and mudstone (right). The data were taken with a 500-MHz antenna in test two. Also shown is the reflection caused by a metal survey flag inadvertently left on the surface. Sandstone bedrock is highlighted with a solid line and the mudstone is identified by the lack of reflections. The location of this 41-m scan, labeled scan 2, is shown in Figure 4.7.

strong distinct reflections. As the antenna was towed toward Pit 2C, over mudstone deposits, the sandstone interface faded and very few radar reflections were recorded.

Mudstone lenses were found in areas in which no radar reflections were seen. Sandstone bedrock provided strong easily recognizable radar reflections. In areas of mudstone parent material, the sandstone reflection rapidly weakened. While the interface between soil and mudstone could not be identified, the sudden disappearance of a sandstone reflection usually indicated the presence of mudstone. Apparently, the high conductivity of the mudstone prevented the radar waves from being reflected to the surface.

The inaccuracy of rock probe data was demonstrated in Site 2. According to the manual rock probe data, Site 2 appeared to have a very irregular bedrock surface in the northwestern corner (Figure 4.7). After excavating Pit 2C in that area, a new parent material, mudstone, was discovered. This dense material is not solid, but usually stopped the manual rock probe before solid bedrock was reached. As a result, the bedrock maps derived from the manual data appeared very irregular. GPR data taken in the northwest corner showed the lack of returning radar signals that was characteristic of areas underlined by mudstone. Instead of an irregular sandstone bedrock surface, as indicated by the manual rock probes, the area was composed of mudstone parent material.

As shown by Collins et al. (1989) and Doolittle et al. (1988), the radar data were more accurate for predicting depth to bedrock than rock probes when an accurate σ is found. These researchers found that dense layers of rock fragments stopped mechanical probes before bedrock was reached. Similar results were noticed on the Cumberland Plateau. Sand from weathered bedrock and dense mudstone lenses stopped the manual rock probes many

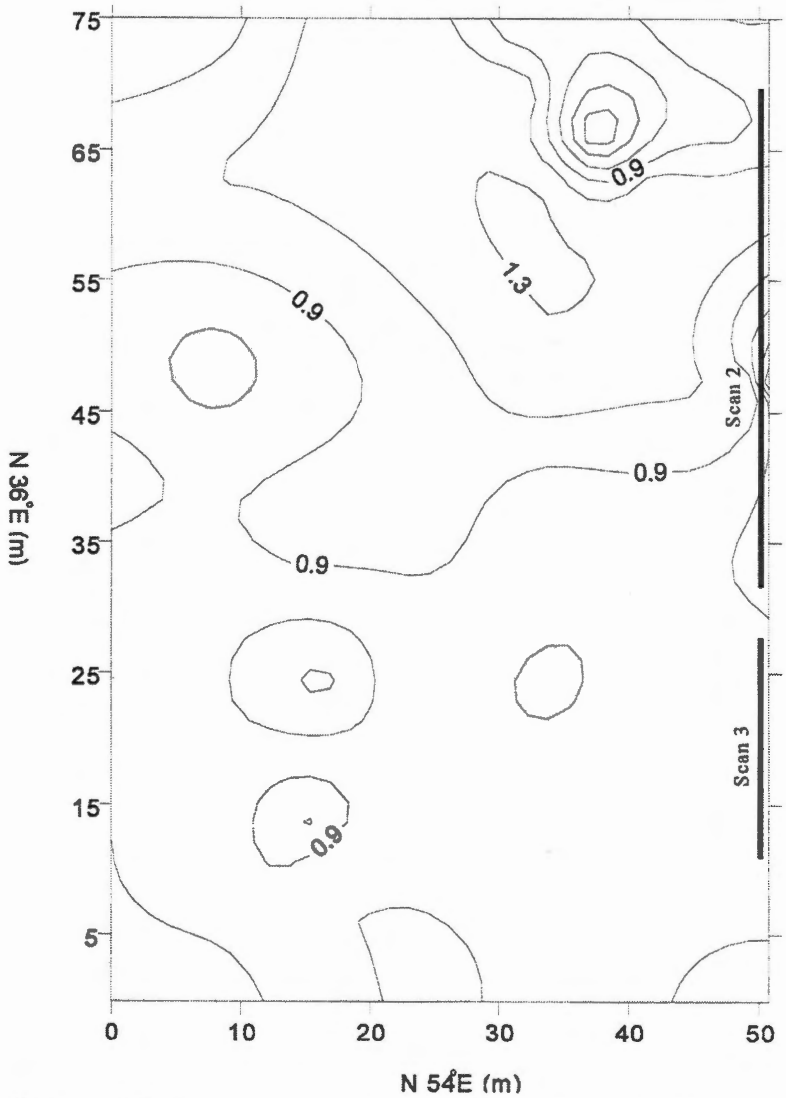

Figure 4.7. Contour map of Site 2 showing soil depth (in meters) taken from a physical survey. Notice the irregular depths in the upper right hand corner caused by faulty depths taken with the rock probe in mudstone.

times before sandstone bedrock was reached.

GPR data taken with the 500-MHz antenna provided information on the transition from soil to bedrock. In some areas of the test sites, soils contained a Cr horizon. The presence of a Cr horizon indicated that a zone of weathered bedrock was present between the soil and sandstone bedrock. The intensity of bedrock reflections was much weaker in soils with a Cr horizon (Figure 4.8) than in soils without a Cr horizon (Figure 4.9).

Test Three

Calibration. To identify soil interfaces near the stream in Site 1, the σ of the soil with similar moisture had to be calculated. The 500-MHz antenna was towed over a pipe inserted horizontally 76.2 cm below the surface into the soil profile of Pit 1A (Figure 4.10). With the known depth of the pipe and a TT of 19.22 ns, the σ of the soil was found to be 14.78.

Horizon Identification The reflection representing the water table was found in the radar data by comparing the physically measured depth to the water table to the radar data. By inserting the σ of the soil into the radar data, the TT recorded by the GPR system were converted to depth. The water table was located by matching reflections in the radar data that occurred at the near the same depth as the physical measurements. To check the data, the scans started with the antenna near the creek. By conducting surveys up the hill away from the creek, the water table would begin at the surface and fall away as the level of saturated soil increased in depth.

In the data, a reflector did appear at the surface and followed the expected pattern

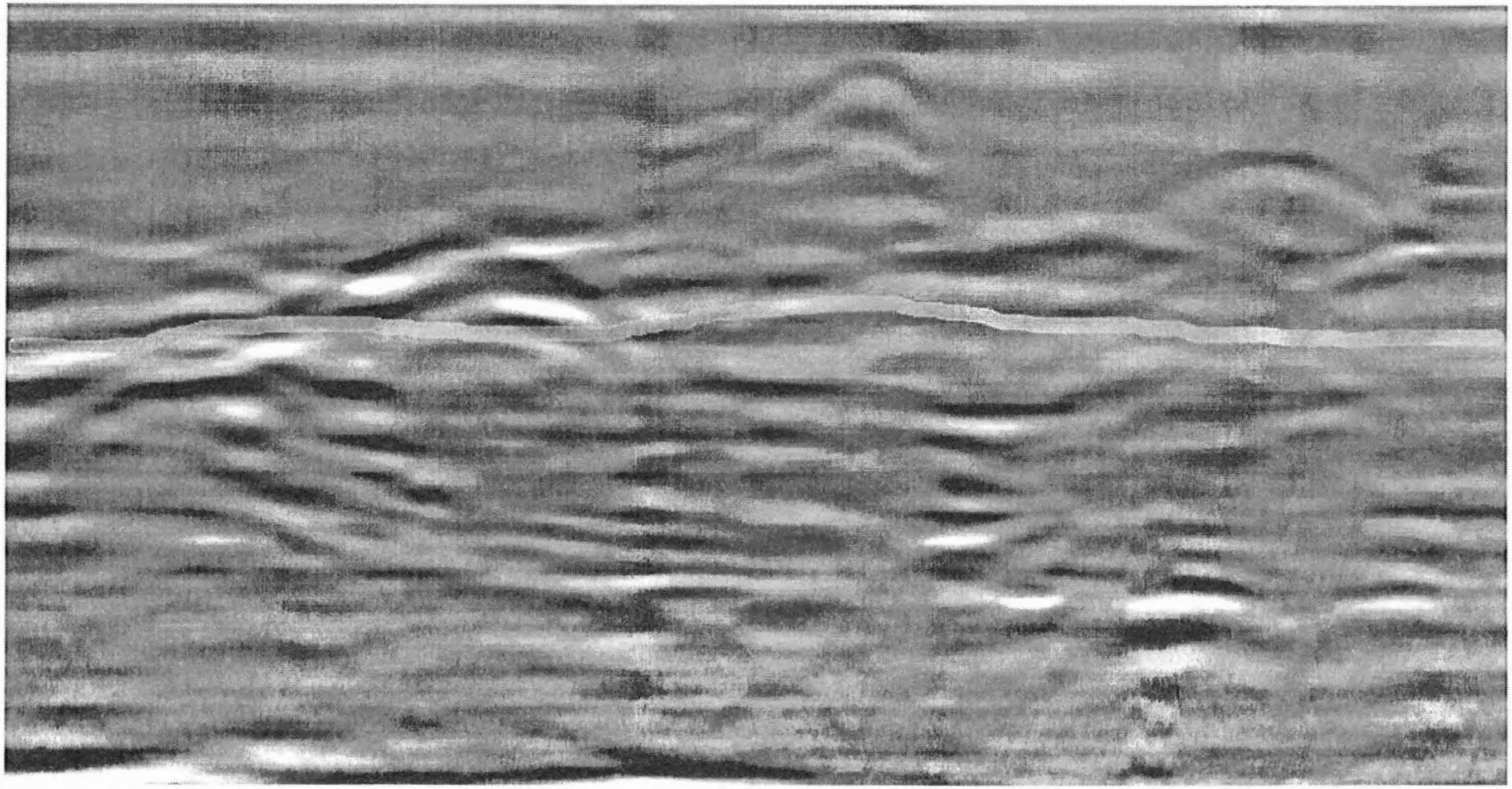

Figure 4.8. GPR data taken at Pit 2A (calibration pit) showing the weak bedrock reflection typical of soils containing a Cr horizon. The data were taken with a 500-MHz antenna in test two. The location of this 5.5-m scan, labeled scan 1, is shown in Figure 3.18.

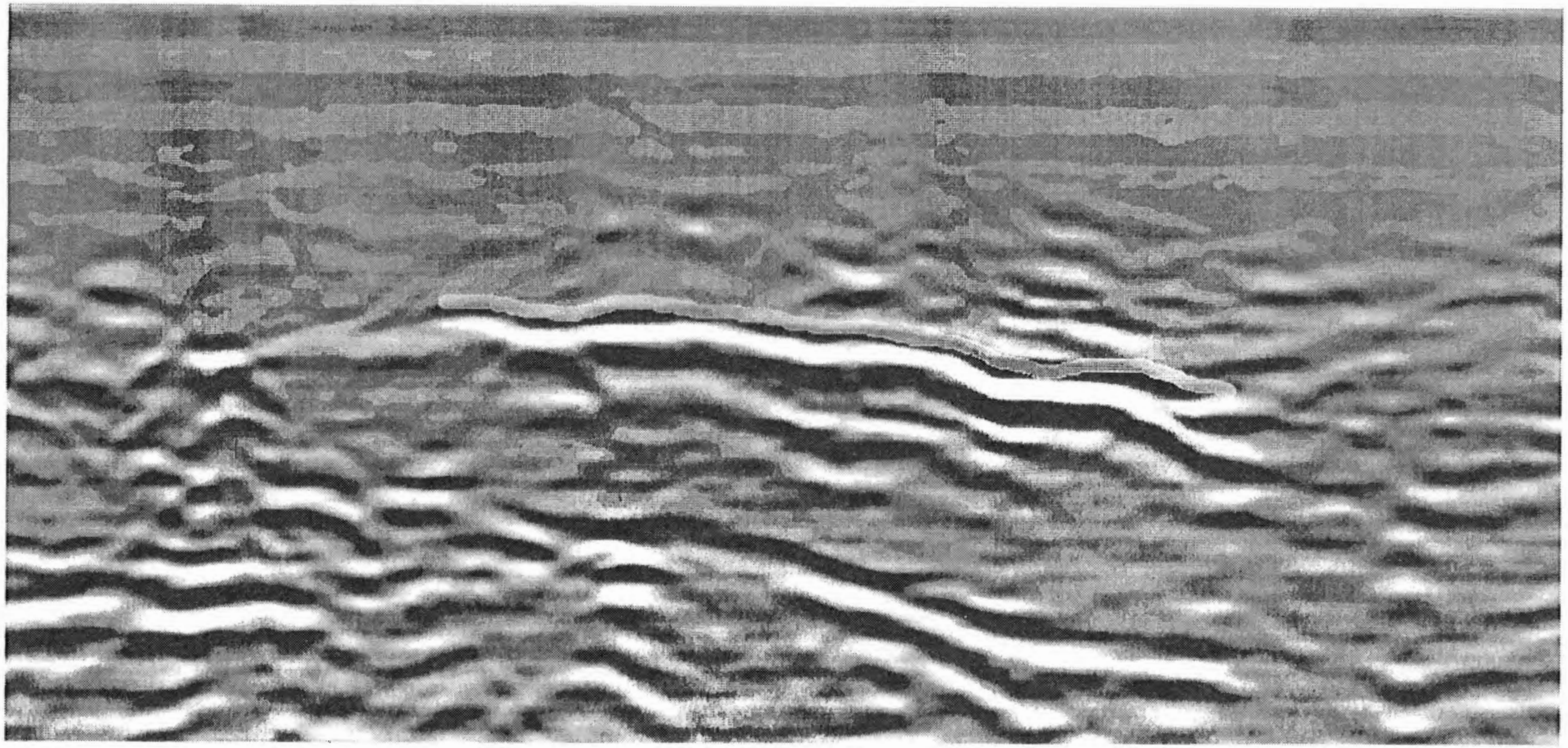

Figure 4.9. Radar data taken adjacent to Pit 2B. The strong reflection highlighted by the solid line provides an example of a sandstone bedrock reflection when a Cr horizon is not present. The location of this 15.5-m scan, labeled scan 3, is shown in figure 4.7.

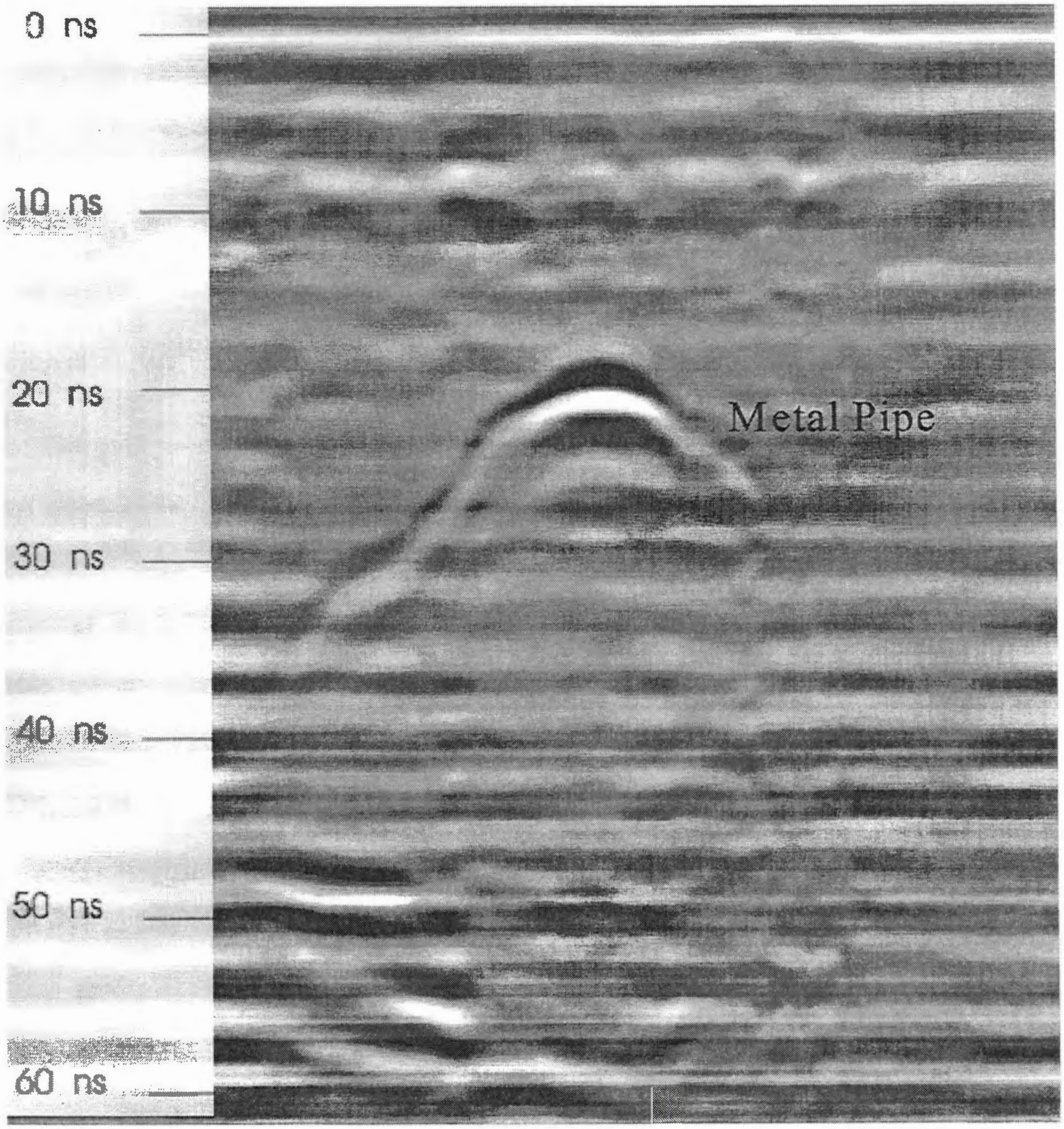

Figure 4.10. Data taken from Pit 1A with a 500-MHz antenna showing a metal rod inserted horizontally at a depth of 0.76 m. The location of this scan, labeled scan 4, is shown in Figure 3.14.

of the water table horizontally for 10 m (Figure 4.11). At this point, the water table was 0.4 m below the soil surface. Once the water table fell to a depth greater than 0.4 m, the image faded from the radar data.

The 500-MHz antenna used in test three resolved sandstone bedrock to depths of 2 m. Horizontal ringing, inherent to some degree in all antennas, was more of a problem with this antenna. This ringing appeared in the data as flat horizonal lines. Depth to many horizons remains constant over large areas and can be confused with the horizontal ringing. True interfaces within the soil can sometimes be picked out by changes in the intensity of the reflected wave. This method of horizon identification was difficult.

Ringing can be removed from the data by applying a horizontal high pass filter during post processing. Applying the filter at the least sensitive value of 255 will remove all reflections and ringing in the data that are flat for more than 255 scans. Signals flat for less than 255 scans will be minimally affected (GSSI, 1994; GSSI, 1992a). This method works well when the interface of interest changes depth in 255 scans as the bedrock on the Cumberland Plateau often does. However, interfaces that remain at the same depth over great distances, such as soil horizons, will be removed from the data by this type of filter. Identification of soil horizons with the 500-MHz antenna was very difficult.

Antennas

Two antennas were used in the study: a 500 MHz and a 900 MHz. Due to the difference in pulse width, each antenna exhibited different qualities. Advantages and drawbacks were apparent with both antennas. The tests showed that selection of the proper

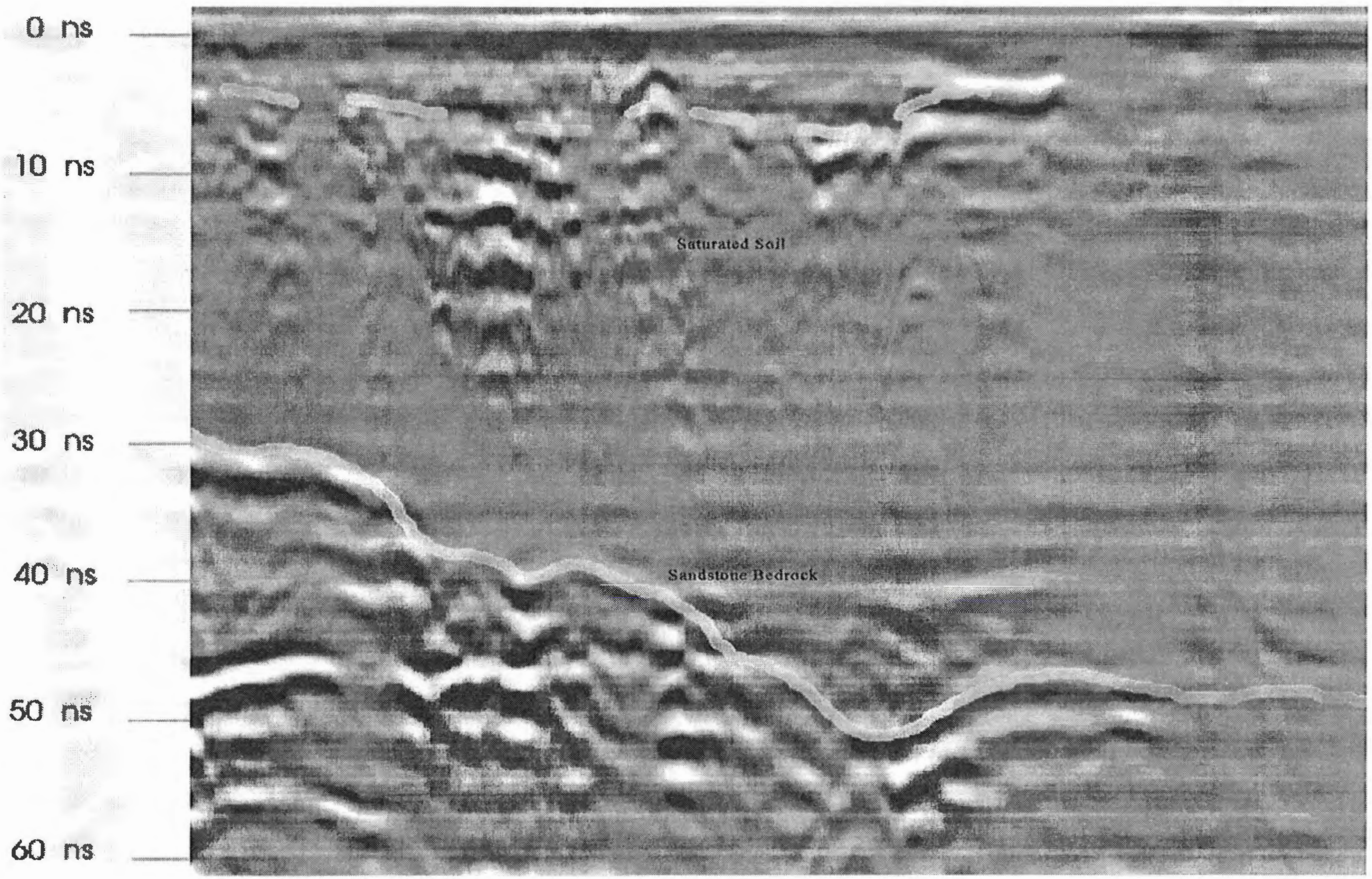

Figure 4.11. Radar data taken near the stream in Site 1 with a 500-MHz antenna. The reflection highlighted by the dashed line appears at approximately the depth of the saturated soil. The reflection highlighted by a solid line appears at approximately the depth of the sandstone bedrock. The location of this 15-m scan, labeled scan 5, is shown in Figure 3.14.

antenna played a key role to the success of a GPR survey. The tests also demonstrated that one antenna was not suited for all GPR surveys.

The 900-MHz antenna proved best for shallow detailed surveys. Because of the narrow pulse width of the antenna, resolution of narrow layers was possible. With the narrow, weakly developed soil horizons of the Cumberland Plateau, the high frequency antenna shows the most promise for future soil horizon surveys in this area. Bedrock surveys with the 900-MHz antenna were impractical. Sandstone bedrock was identified with the 900-MHz antenna when soil depth was less than 1 m. However, in many cases, soil depth was greater than 1 m. The high frequency antenna lacked the ability to profile bedrock under these conditions. Data interpretation was more difficult with the higher frequency antenna. The many narrow, horizontal bands produced by the 900-MHz antenna made identification of true interfaces more difficult.

The 500-MHz antenna proved best for bedrock surveys. Penetration depths of up to 2 m were possible. Sandstone bedrock was within 2 m of the surface in 14 of the 15 soil pits in the test sites. Sandstone bedrock produced strong reflections that were easily tracked with the lower frequency antenna.

High resolution data were collected with the 500-MHz antenna. Even though the pulse width of the 500-MHz antenna was wider than the 900-MHz, highly resolved data were obtained. Many of the same interfaces within the soil were visible on data taken with both the 500-MHz antenna and the 900 MHz. Due to the wider pulse width, fewer horizontal lines were visible in data taken with the 500-MHz antenna. Bands representing electrical interfaces were generally wider, easier to identify, and easier to follow.

2. GPR Survey Methods

Test One

By operating the mainframe from a stationary location, the survey area was limited to about a 20-m radius. Towing by hand did allow the spacing of the transect lines to be very close for a highly detailed survey. The path of the antenna and the insertion of marks to provide a horizontal reference in the data were monitored closely during hand towed surveys. Towing the antenna at a constant speed by hand was difficult. Variation caused by slight changes in speed was corrected during post processing.

Radar surveys from a stationary position proved effective on the Cumberland Plateau. This type of survey allowed very tightly spaced transects for high accuracy and precision. Stationary radar surveys would best be suited for location of point objects within the soil or for very small, very localized soil irregularities.

Test Two

The ATV used in the second test provided a large enough base to transport the radar equipment and operators while towing the antenna, yet was rugged and maneuverable enough to cover all the terrain. By mobilizing the entire radar unit, very large quantities of data could be collected very rapidly. One transect in Site 3 covering 170 m could be surveyed in about five min. This transect provided continuous subsurface data for the length of the scan and required more than ten megabytes of memory. Due to the size of the ATV and the sled containing the antenna, controlling the path of the antenna was more difficult. Heat, rain, and glare were also problems in the top less ATV. Longer surveys, made possible with the ATV, allowed areas to be found in which the depth to subsurface interfaces changed. These areas allowed more definite identification of subsurface characteristics.

Mobile GPR surveys from an ATV provided a very effective method of gathering vast amounts of subsurface data in rough terrain. The ATV limited maneuverability in small areas but allowed accurate transportation of the antenna over large areas. Because of this, an ATV based mobile survey may not be the best method of finding small point objects, but it is suited to surveying large interfaces such as those present in the soil.

Test Three

The covered pick-up truck used in the third test provided a mobile, weather-proof base of operation. The radar mainframe, battery cart, monitor and operator all fit in the bed of the truck. The truck was less mobile than the ATV, but it provided excellent protection against environmental extremes and against glare. Even though the truck was less maneuverable than the ATV, it worked well for long straight surveys. Surveys were also conducted more efficiently when the truck was used to pull the antenna because the need to move the radar equipment from one vehicle to another was eliminated. By eliminating the need to move the equipment into an ATV, approximately 30 min were saved in both set-up and take-down time.

3. Physical survey methods

The shallow wells in Site 1 provided an effective method for monitoring the level of saturated soil in the area. PVC tubes prevented soil from filling the wells for more than one year. Detection of the water table with the electronic probe proved successful for locating the level of the saturated soil. Removal of cobwebs and other blockage caused by insects was necessary to prevent the water probe from sounding prematurely. Surface water was prevented from entering the well directly by capping the tube and tightly packing soil around the tube. This packed soil caused rain water to flow away from the shallow well.

Probing for bedrock manually was the most difficult part of the survey. In many cases, manual probing was not only time consuming, but inaccurate. The probe worked well in areas where the transition between soil and solid bedrock was abrupt and occurred at depths less than 1 m. As depth to bedrock became greater than 1 m, the rod became more difficult to insert into the soil. In these situations, very little horizontal resistance was required to stop the probe. Layers of sand or weathered bedrock also stopped the probe prematurely. Lenses of dense mudstone underlying the soil caused the greatest problem with the manual rock probe. Due to the density and depth of the mudstone, the probe was usually stopped. Distinguishing between mudstone and weathered sandstone with the rock probe was difficult.

4. GPR Applications

GPR effectively identified the depth of soil over sandstone bedrock on the Cumberland Plateau. Argillic horizons, perched water tables, and mudstone lenses were also found. Nondestructively locating and tracking these features can allow GPR to be used in several practical applications. Soil surveys, site selection for excavation projects, site-specific farming, and location of on-site domestic wastewater renovation systems could all be optimized with data that can be provided with GPR.

GPR provides a method of collecting soil data that will increase the precision of soil surveys while decreasing the time required in the field. Depth to sandstone bedrock and the presence of an argillic horizon are key factors in classification of Cumberland Plateau soils. Due to time and money constraints, the number of points physically sampled by soil scientists in the field is limited. As shown in Figure 4.12, GPR identified changes in the subsurface characteristics of the soil. With this knowledge, the placement of the limited number of physically sampled sites can be optimized and reduced. GPR also provides continuous subsurface data on identifiable characteristics between the physically sampled points.

Shallow soils, typical of the Cumberland Plateau, greatly increase the volume of bedrock that must be removed during excavation projects (Freeland et al,. In Press). Blasting through solid sandstone bedrock is considerably more expensive than excavation of soil. In the case of many farm structures, site selection is flexible. Placement of excavation sites on areas where deep soils are present could greatly reduce the cost of land preparation. Shown in Figure 4.13, GPR identified and tracked solid sandstone bedrock. With a 500-MHz antenna, GPR has proven effective at finding sandstone bedrock to depths of 2 m. Pre-site surveys with radar could provide an effective method for placement of construction sites so that excavation costs are reduced.

GPR shows promise as a tool to aid with site-specific farming. With global positioning systems, farmers can apply chemicals at variable rates throughout fields. To

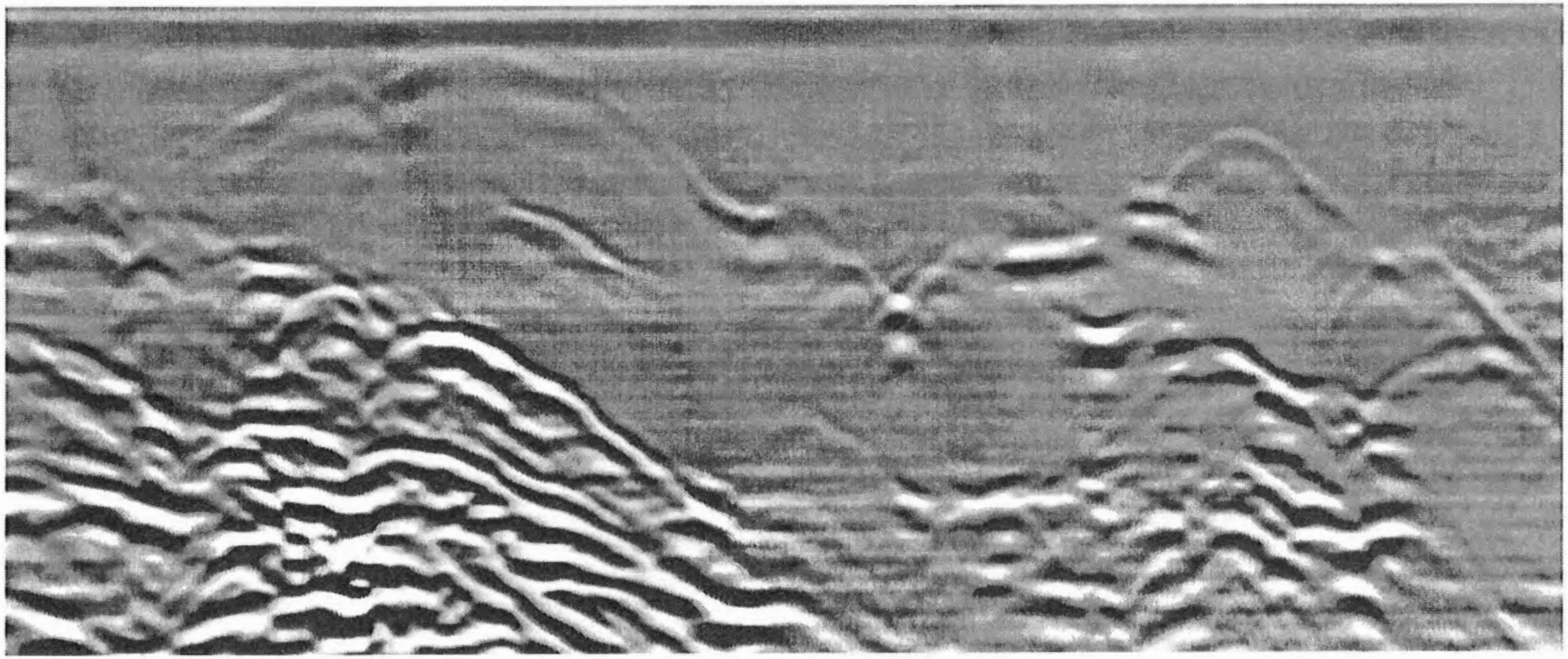

Figure 4.12. An example of radar data taken in test two from Site 3 with a 500-MHz antenna showing change in soil depth. The location of this 19-m scan, labeled scan 6, is shown in Figure 3.16.

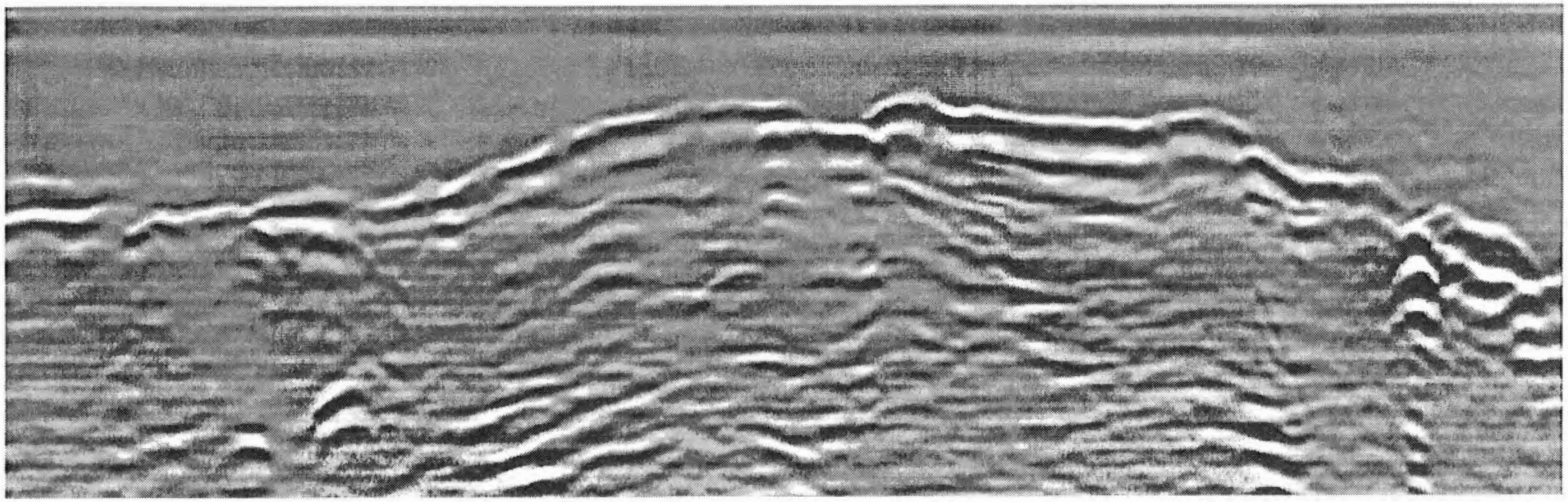

Figure 4.13. An example of radar data taken in Site 3 with a 500-MHz antenna showing a clear reflection of solid sandstone bedrock. The location of this 25.5-m scan, labeled scan 7, is shown in Figure 3.16.

apply site-specific farming effectively, a great deal of information must be gathered throughout the field that is to be farmed. GPR provides a method of collecting continuous data on soil depth, saturated soil depth, and depth to the argillic horizon on the Cumberland Plateau.

Information gathered with GPR could be used in situating on-site domestic wastewater treatment systems. Most conventional domestic treatment systems consist of a septic tank and a distribution field. The effluent from the septic tank is distributed across the soil by the distribution field. As the effluent flows downward through the soil, the microorganisms oxidize the contaminants and purify the water. To ensure the water is cleaned properly, the state of Tennessee requires that the effluent pass through a minimum of 1.22 m of soil before reaching bedrock or saturated soil (The University of Tennessee Agriculture Extension Service PB 1472, not dated). Radar surveys in a tightly spaced grid, as in test one of this study, could be used to effectively position the distribution fields so that they meet the requirements of the state.

GPR offers promise as a valuable tool to be used in other soil and water research. Traditionally, destructive sampling was the primary method to gather information about the soils subsurface properties. Many times this destructive sampling disturbs or destroys the natural properties of the soil that are under investigation. With GPR as a sampling tool, information can be gained about the subsurface properties without physically disturbing their natural state.

Chapter 5

Recommendations

1. GPR Survey Recommendations

Antenna Selection

Proper antenna selection was critical to the success of GPR surveys. Antennas were selected based on soil type and survey objective. Relatively high frequency antennas (500 MHz and 900 MHz) were selected to resolve the narrow, weakly developed soil horizons of the Cumberland Plateau. Sandy, shallow soils, characteristic of the Cumberland Plateau, provided a medium for successful GPR surveys with the high frequency antennas that would not have been possible in deeper soils with higher clay content.

The 900-MHz antenna provided the best data for shallow surveys that required high sensitivity and resolution. Transitions between horizons occurring in the top 0.75 m of the soil were found with the 900-MHz antenna. The primary soil feature of interest in this zone was the argillic horizon. This horizon normally occurred between 15 and 20 cm from the surface and was often lost in the wider ground wave of lower frequency antennas. Reflections were also seen in radar data collected with the 900-MHz antenna near the depth of BC and Cr horizon interface. Because of the shallow penetration of the 900-MHz antenna, bedrock surveys were possible only in areas with soil depth less than 0.75 m.

The 500-MHz antenna provided the best results for bedrock and other deep (0-2 m) surveys. Two meter penetration depths of the lower frequency antenna allowed bedrock to be resolved in most areas of the test sites. Sandstone bedrock produced the strongest radar reflections in the test sites. Areas underlined by mudstone produced virtually no radar images. Even though the interface between soil and mudstone was not identified, mudstone was located by the abrupt change from a strong sandstone reflection to the absence of reflections. Interfaces near the depth of the argillic horizon were also recorded with the 500-MHz antenna. The boundary between the Cr and BC horizon was not visible in data taken with the lower frequency antenna. The presence of a Cr horizon was indicated by weak sandstone reflections.

Unit Settings

Based on these tests, the recommended settings for GPR surveys on the Cumberland Plateau are shown in Table 5.1. When setting the survey range, the best results were obtained by adjusting the radar unit to scan slightly deeper than the interface of interest or slightly beyond the antenna's range. Setting the range slightly deeper than required insured that data near the limit of the antenna or at the interface of interest was not lost. Proper setting of the trace position (start of scan) was of particular importance with the 900-MHz antenna. Due to the small pulse width of the 900-MHz antenna, the position servo failed to function properly. Ordinarily, the position servo placed the ground wave at the top of the radar scan. With the high frequency antenna, the servo often locked on signals other than the ground wave. Lifting the antenna off the ground while observing the radar image helped to

Table 5.1. Recommended SIR System-10A settings for GPR surveys on the Cumberland Plateau.

Setting	Survey Target: Shallow Features	Survey Target: Bedrock/Mudstone
Antenna		
Model	3101D	3102
Rated Frequency (MHz)	900	500
Pulse Width (ns)	1.1	2
Range (ns)	30	60
Scans per Second	49.984	49.984
Samples per Scan	256	512
IIR High Pass Filter		
Poles	2	2
Frequency	4	5
IIR Low Pass Filter		
Poles	2	2
Frequency	54	55
Horizontal Low Pass Filter	3	5

ensure that the proper start of scan position was found. If the antenna was properly set, the TT of the radar wave to the soil surface would increase as the antenna was raised further from the surface.

Survey Method

Three methods of surveying with GPR were tested in this study. First, the mainframe was set up in a stationary location and the antenna towed by hand. Next, the radar mainframe was mounted in an open air ATV and the antenna towed behind. Finally, a covered pickup truck was used to transport the mainframe and pull the antenna. Advantages and disadvantages were apparent with each method of surveying.

Towing the antenna by hand while the radar system was operated from a stationary location proved effective for surveys of small areas. The survey area was limited by the length of the control cable connecting the radar unit to the antenna. Surveying with the radar unit in a stationary location allowed close transect spacing and accurate placement of the horizontal reference marks. This type of GPR survey would work best for surveys that require a high degree of detail, such as locating the exact boundaries of small buried objects (waste burial sites, pipes, septic tanks, etc.).

GPR surveys with the radar unit mounted in an ATV were better suited for large areas of rough terrain. The ATV allowed rapid collection of radar data over a wide variety of terrain. Good maneuverability and visibility were possible from the ATV. Surveys based from this type of vehicle would work well for large scale soil surveys or general location of buried objects within a large area.

A covered pick-up truck proved useful for surveys in moderate terrain. The covered truck provided excellent protection from environmental factors. Mobility was limited by the size of the vehicle. This method of conducting a GPR survey worked well for large geological and soil investigations. Surveys conducted from the truck worked well in the maintained pastures of the Cumberland Plateau.

Horizontal reference points were necessary to link the radar data to a physical location in the test site. Placement of markers such as survey flags or paint spots worked well for small surveys. However, this method of spatial calibration was not efficient for larger surveys, such as in test two. Natural or manmade landmarks provided an excellent horizontal reference for GPR surveys that do not require precise horizontal control. One method of greatly increasing the efficiency and spatial precision of future surveys would be to mount a GPS unit on the vehicle towing the antenna. By combining GPS and GPR, the exact location of all the subsurface data would be recorded during surveying.

Calibration

Calibration pits were used to convert the TT stored in the radar data to depth. Scans taken over buried objects of known depth provided a method of calculating the σ of the soil. With the σ and the TT of the radar wave, the depth to subsurface interfaces could be found. If the σ of the soil changed as depth increased, depth predictions were based on calibrations on objects at near the same depth as the point of interest.

Images in the radar data were also identified during the calibration process. By inserting pipes into the soil at a point of interest, reflections near that depth could be found.

However, this method of interface identification left a great deal of uncertainty. Distinguishing between true subsurface interfaces that were horizontal and horizontal ringing inherent to the system was difficult. Longer scans taken after calibration over the metal pipes allowed changes in the radar data to be compared to changes in depth to the interface of interest. Noise inherent to the system remained at a constant TT, while the TT to true images varied according to the depth of the interface. If possible, calibrations in areas where near-surface interfaces are changing in depth will provide the most dependable method of identifying the interfaces.

2. Additional Research

Experience was one of the greatest limiting factors in the tests conducted in 1995. The researchers had to learn to set up and operate the radar system as well as interpret the data before any of the established objectives could be met. As previously noted by Doolittle (1987), GPR is site and user dependent. As experience with the GPR system increased, set up and data interpretation became better. Future tests, after more experience with radar is gained, will provide better data.

Several objectives were set for this test as a beginning for GPR research on the Cumberland Plateau. Preliminary objectives included familiarization with the equipment and the survey site. Another goal was development of a power supply and method of transportation for the radar system. The last focus of the study was to learn which soil horizons could be identified with GPR. With the knowledge of the equipment and site that was gained in this test, future tests should be limited to selected soil properties. Limiting the scope of the research would allow more extensive lab analysis of the soil properties to determine which soil characteristic caused the radar reflection.

Reflections were recorded in the radar data at approximately the depth of the Ap and Bt transition. The NRCS soil scientists that described the soils noted that while the clay content was enough to classify the horizon as argillic, the clay content of the soil was still very low. Laboratory analysis of the soil is recommended to determine what property of the soil caused the reflection.

Further water table surveys with GPR were also recommended. In test three, the water table was identified near the surface and tracked to a depth of .4 m. At this point, the reflection disappeared. Soil samples should be taken in small increments from the surface to the level of saturated soil. Each sample should be tested for moisture, sand, silt, and clay content. This data would provide information on soil characteristics and the capillary fringe that could explain the disappearance of the water table from the radar data.

Mudstone was repeatedly found on the Cumberland Plateau with radar. Areas in which no radar waves returned to the surface were usually underlined by mudstone. This observation indicated that the mudstone must be so conductive that most of the radar waves were attenuated. Future tests with lower frequency antennas were recommended to attempt to probe below the mudstone deposit. Lab analysis of the mudstone to determine conductivity and σ could provide information useful in locating the interface between soil and mudstone in future GPR surveys.

With the knowledge gained in this test, GPR can be used as a tool to aid in selection of test sites in future research. Positive identification of reflections that remain at a constant depth is difficult. Even without calibration, GPR was useful for finding locations where subsurface characteristics change in depth. Placement of future test sites in areas where depth to a particular soil characteristic is changing will allow more definite identification of the interface.

Sandstone bedrock produced such a strong reflection in most radar data that a general idea of soil depth could be gained with limited calibrations. Deep soil is one indicator of the presence and development of soil horizons. By selecting future test sites based on both surface observations and preliminary GPR data, the presence of identifiable soil horizons will be increased.

Post processing of radar data can enhance subsurface images while reducing static and noise inherent to most radar systems. Methods and computer software for post processing are rapidly advancing. Several post processing techniques were used during this study. Most were designed to scale the data horizontally to compensate for changes in forward velocity during surveying. Other methods used were designed to remove horizontal ringing, or flat bands, characteristic to many antennas. This method is useful if the image of interest changes in depth regularly. If the image of interest is horizontal, this method of processing cannot be used. More complicated processing techniques are available or are becoming available everyday. Further studies in post processing radar data are recommended.

3. Statistical Comparison

GPR has proven to be an accurate method of collecting data on various soil properties. Truman et al. (1988) found that the relationship between the measured depth to an argillic horizon and the depth taken from scaled GPR data was linear and had a correlation coefficient of 0.94. Truman et al. (1988) also noted that the measured depth to the water table in a coarse soil formed a linear relationship with depths taken from scaled radar data. The correlation coefficient between the GPR data and the measured depth to the water table was 0.98. In other research, Johnson et al. (1979) found that comparisons between GPR data and physical measurements in areas with uniform horizons were within ± 2.5-5 cm. In one test, Collins et al. (1989) found that 87% of the soil depth predictions based on radar data were within 10 cm of the actual soil depth, while only 7% of the auger data was within 15 cm of the actual soil depth. The actual soil depth in this test was found by excavating a ditch after the GPR data was taken. In a wetting front study, Vellidis et al. (1990) found that the depth to the wetting front was within 8 cm of 91% of the samples taken.

In the test previously noted by Truman et al. (1988), comparisons between radar data and physically measured data were linear and had high correlation coefficients. Truman et al. (1988) points out that for accurate depth measurements to be taken from GPR data abrupt changes in dielectric constant must be present. Truman et al. (1988) also notes that in order for depths taken from GPR data to be accurate the radar must be calibrated every time the soil type or conditions change. As a result of the test by Truman et al. (1988), the objectives of this test were primarily to become familiar with the GPR equipment, develop survey and calibration procedures, and determine which subsurface characteristics would produce a radar reflection. With the calibration procedures and pits developed in this test and soil tests in the lab, future GPR data can be statistically compared to selected soil properties at the test sites on the Cumberland Plateau. Before statistical comparisons between ground truth and radar data can be made, several problems must be addressed.

One problem with making statistical comparisons between physical data and GPR data was obtaining accurate ground truth data. Accurate soil depth measurements were made from soil pits and with the rock probe in areas where the transition from soil to bedrock was abrupt and shallow. However, areas that contained a layer of dense sand caused by the weathering of sandstone bedrock prematurely stopped the rock probe. Areas underlined by mudstone allowed the rock probe to penetrate a short distance. During physical surveys, distinguishing between the layer of weathered sandstone and the mudstone was difficult.

Physical data taken from soil pits in this test were gathered prior to acquisition of the radar equipment. As a result, the radar data were taken from an area adjacent to the pit. Future sites for GPR surveys should be scanned with the GPR prior to disturbing the soil. By surveying with the GPR before digging the pits, physical descriptions would be provided of the same soil profile that was surveyed with radar. Metal pipes should then be inserted into the soil to provide a depth reference.

Chapter 6

Summary

The purpose of this study was to evaluate GPR for soil applications on the Cumberland Plateau. For three test sites on the Cumberland Plateau, the study had the following objectives:

1. To identify the subsurface characteristics that can be resolved using GPR,
2. To design, develop, and evaluate GPR survey methodologies for the Cumberland Plateau region, and
3. To formulate recommendations, specific for the desired subsurface targets, concerning survey procedures, equipment and settings.

Radar images were recorded at the approximate depths of the argillic horizon and the horizon of weathered sandstone with the 900-MHz antenna. The 900-MHz antenna provided the highest resolution data but allowed the least penetration. Because of the limited penetration of the 900-MHz antenna, bedrock surveys were not practical.

The 500-MHz antenna provided greater penetration with slightly reduced resolution. Reflections were recorded at approximately the depth of the Bt horizon, the bedrock, and the level of saturated soil. Several features of the parent material could be predicted by the presence and strength of the sandstone bedrock reflection. Abrupt changes from soil to solid sandstone produced the strongest radar images recorded in the study. The presence of a Cr horizon, or zone of weathered bedrock produced weaker, less distinct images. Soil underlined by mudstone produced no radar reflection at all. Sandstone bedrock was tracked to depths

of 2 m. Images at approximately the depth of the saturated soil were recorded and tracked until the water level fell to 0.4 m below the soil surface. After the depth to the water table became more than 0.4 m, the image no longer appeared.

Low clay content and shallow soil typical of the Cumberland Plateau provided an excellent medium for GPR investigations. Strong, distinct reflections could be located and tracked throughout the test sites. The σ of the soil in the test sites was 11.7-14.7. The calibrations were based on metal pipes inserted horizontally into the soil at known depths. Data for the calibrations were taken on three different days at two separate pits.

Three methods of gathering data with GPR were tested. First, the antenna was towed manually and the radar control unit was operated from a stationary location. This type of survey allowed accurate control of the antenna's path and the insertion of marks for horizontal scaling. In the second test, the antenna was mounted in an ATV. Large areas of rugged terrain were rapidly surveyed from the ATV. In the last test, the radar system was mounted in the bed of a covered pick-up truck. This method of scanning allowed rapid surveys to be conducted in mild to moderate terrain while protecting the radar equipment from environmental extremes.

The primary factors affecting antenna selection depended on the objectives of the survey. The 900-MHz antenna provided the best results for shallow surveys requiring resolution of narrow interfaces, such as soil horizons on the Cumberland Plateau. A range setting of 30 ns was usually employed with the high frequency antenna. Lower frequency antennas, such as the 500-MHz antenna used in this test, were required for bedrock and other

Bibliography

Bibliography

1. Barr, G. L. 1993. Application of ground-penetrating radar methods in determining hydrogeologic conditions in a karst area, West- Central Florida. U. S. Geological Survey. Water-Resources Investigations Report 92-4141.

2. Brown, R. B. 1985. The need for continuing update of soil surveys. Soil and Crop Science Society of Florida Proceedings. Volume 44: 90 - 92.

3. Collins, M. E., and J. A. Doolittle. 1987. Using ground-penetrating radar to study soil microvariability. Soil Science Society of America Journal. 51: 491-493.

4. Collins, M. E., G. W. Schellentrager, J. A. Doolittle, and S. F. Shih. 1986. Using ground-penetrating radar to study changes in soil map unit composition in selected histisols. Soil Science Society of America Journal. 50: 408-412.

5. Collins, M. E. , J. A. Doolittle, and R. V. Rourke. 1989. Mapping depth to bedrock on a glaciated landscape with ground-penetrating radar. Soil Science Society of America Journal. 53: 1806-1812.

6. Doolittle, J. A., 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. Soil Survey Techniques. Special Publication No. 20.

7. Doolittle, J. A., R. A. Rebertus, G. B. Jordan, E. I. Swenson, and W. H. Taylor. 1988. Improving Soil-landscape models by systematic sampling with ground-penetrating radar. Soil Survey Horizons. Summer: 48-52.

8. Freeland, R. S., J. C. Hamlett, J. Loy. In Press. Trench Silos--Minimizing Excavation Cost on Sites Having Shallow Soils Using Underground Imaging. Tennessee Agri-Science. Tennessee Agricultural Experiment Station, Knoxville, TN.

9. GSSI., 1992a. RADAN III Instruction Manual. North Salem, NH 03073-0097: P. O. Box 97.

10. GSSI., 1992b. SIR System-10A Training Notes. North Salem, NH 03073-0097: P. O. Box 97.

11. GSSI., 1993. SIR System-10A User's Manual. North Salem, NH 03073-0097: P. O. Box 97.

12. GSSI., 1994. RADAN Training Notes. North Salem, NH 03073-0097: P. O. Box 97.

13. Johnson, R. W., R. Glaccum, and R. Wojtasinske. 1979. Application of ground penetrating radar to soil survey. In *Proc.* Soil and Crop Science Society of Florida, 68-72. Volume 39. 2-4 October.

14. Kung, K.-J. S. and Z. -B. Lu. 1993. Using ground-penetrating radar to detect layers of discontinuous dielectric constant. Soil Science Society of America Journal. 57: 335-340.

15. Miller F. P. 1978. Soil survey under pressure: the Maryland experience. Journal of Soil and Water Conservation. May - June.

16. Olson, C. G., and J. A. Doolittle. 1985. Geophysical techniques for reconnaissance investigations of soils and surficial deposits in mountainous terrain. Soil Science Society of America Journal. 49: 1490-1498.

17. Schellentrager, G. W., J. A. Doolittle, T. E. Calhoun and C. A. Wettstein. 1988. Using ground-penetrating radar to update soil survey information. Soil Science Society of America Journal. 52: 746-752.

18. Shih, S. F. and J. A. Doolittle. 1984. Using Radar to investigate organic soil thickness in the Florida Everglades. Soil Science Society of America Journal 48: 651-656.

19. Smith M. C., G. Vellidis, D. L. Thomas, M. A. Breve. 1992. Measurement of water table fluctuations in a sandy soil using ground penetrating radar. Transactions of the ASAE 35(4): 1161-1165.

20. Soil Survey Staff. 1992. Keys to Soil Taxonomy. Blacksburg, Virginia: Pocahontas Press, Inc.

21. Truman, C. C., H. F. Perkins, L. E. Asmussen and H. D. Allison. 1988. Using ground-penetrating radar to investigate variability in selected soil properties. Journal of Soil and Water Conservation. July-August: 341-344.

22. Truman, C. C., D. D. Bosch, H. D. Allison, and R. G. Fletcher. 1994. Uses of Ground-Penetrating Radar in the Georgia Coastal Plain. USDA ARS-124.

23. Ulriksen, C. P. F. 1982. Application of Impulse Radar to Civil Engineering, PhD thesis, Lund University of Technology, Lund, Sweden, published in U. S. by GSSI.

24. The University of Tennessee Agriculture Extension Service. On-Site Wastewater Treatment Systems. Agriculture Extension Service PB 1472.

25. Vellidis, G., M. C. Smith, D. L. Thomas, L. E. Asmussen. 1990. Detecting wetting front movement in a sandy soil with ground-penetrating radar. *Transactions of the ASAE* 33(6): 1867-1873.

26. Zobeck, T. M., J. G. Lyon, D. R. Mapes and A. Ritchie, Jr. 1985. Calibrating Ground Penetrating Radar Data for Soil Applications. *Soil Science Society of America Journal* 49:1587-1590.

Appendices

Appendix A

Pit 1A Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-18	10YR4/3	L
Bt 1	18-36	10YR4/4	CL
Bt 2	36-51	10YR5/4	CL
Bx	51-114	2.5Y5/6	SL

* Bx...CMD 10YR5/6 and CMP10YR6/3

Pit 1B Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-10	10YR4/3	L
Bt	10-51	10YR5/6	CL
BC	51-71	10YR5/8	SL
C	71-81	10YR5/8	SL
R	81	Sandstone	Bedrock

* BC Few soft sand fragments
* C 30% soft sand fragments

Pit 1C Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-20	10YR4/3	L
Bt 1	20-38	10YR4/4	L
Bt 2	38-56	10YR5/4	L
Bx	56-91	10YR5/4	L
R	91	Sandstone	Bedrock

* Bx...CID 10YR5/8 and CIP 10YR6/2

Pit 1D Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
AP	0-25	10YR3/4	L
Bt 1	25-56	10YR5/8	CL
Bt 2	56-79	10YR5/6	CL
BC	79-112	10YR5/6	SL
R	112	Sandstone	Bedrock

* Bt 2 20% sand fragments.
  BC 7.5YR5/6 Mottles and 50% sand fragments.

Pit 1E Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-13	10YR4/3	L
Bt 1	13-30	10YR4/4	CL
BC	30-51	10YR6/4	CL
Cr	51-81		
R	81	Sandstone	Bedrock

* BC...30%, <5" in diameter sandstone Fragments.

Pit 2A Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-13	10YR3/3	L
Bt 1	13-43	10YR4/4	L
BC	43-64	10YR5/6	SL
Cr	64-76	Soft	Sandstone
R	Sandstone	Bedrock	

Pit 2B Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-18	10YR4/3	L
Bt 1	18-43	10YR 4/4	GR-L
BC	43-58	10YR5/4 C2D10YR6/3	GRV-SL
C	58-66	10YR4/4	GRX-SL
R	66	Sandstone	Bedrock

* Bt 1...15% Sandstone gravel.
BC....50% Sandstone gravel
C........60% Sandstone gravel

Pit 2C Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-10	10YR4/3	L
Bt 1	10-33	10Yr5/4	CL
Bt 2	33-63	10YR6/6	CL
2BC	63-79	Brownish Yellowish Reddish	SiCL
2Cr	79		

* 2Cr Multicolored Clayey Mudstone

Pit 2D Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-18	10YR4/3	L
Bt 1	18-43	10YR5/4	L
2Bt 2	43-71	7.5YR5/6	SiCL
2Bt 3	71-102	10YR6/6	C
3Cr	102-112	Multicolored	Soft Sand-

*Mottles 2Bt2 CFD5YR5/6, CFD10YR6/6,
2Bt3 FFP10YR6/3, FFP7.5YR5/6

Pit 2E Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-18	10YR4/3	L
Bt 1	18-36	10YR4/4	L
Bt 2	36-56	10YR5/4	L
BC	56-76	CMD7.5YR5/6 10YR5/6	GR-L
R	76	Sandstone	Bedrock

*BC...40% Flat gravels.

Pit 2F Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-10	10YR4/3	L
Bw	10-41	10YR4/4	L
BC	41-76	10YR5/4	LS
R	76	Sandstone	Bedrock

* BC...MM&C 10YR6/4 mottles.

Pit 3A Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-18	10YR4/3	L
Bt 1	18-41	10YR4/4	CL
Bt 2	41-71	10YR4/4	CL
BC	71-76	10YR5/4	L
R	76	Sandstone	Bedrock

* Bt2 FFF10YR6/4

Pit 3B Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-20	10YR4/3	L
Bw 1	20-41	10YR5/4	L
Bw 2	41-64	10YR5/4	SL
BC	64-76	10YR5/6	SL
R	76	Sandstone	Bedrock

Pit 3C Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-20	10YR4/3	L
Bw	20-48	10YR4/4	L
BC	48-69	10YR5/6	GR-SL
Cr	69-76	Soft	Sandstone
R	76	Hard	Sandstone

* BC 30% sand gravel

Pit 3D Horizon Description

HORIZON	DEPTH	COLOR	TEXTURE
Ap	0-13	10YR4/3	L
Bt	13-48	10YR5/4	L
Btx	48-81	10YR5/6	L
BC	81-97	10YR5/8	SL
R	97	Sandstone	Bedrock

* Btx...CFD10YR6/2
BC...CFD7.5YR5/6

Appendix B

Raw Data File Names

Test	File Name
Test one	CRSV4_95.001
Test two	CRSV7_95.010
Test three	CRSV8_95.014

GPR Data Used in Figures

Figure	Raw Data	Processed Data	WordPerfect File
1.3	PIT1A2.DZT	PIT1A2_2.TIF	FIG1_3.WP6
4.1	PIPE2.DZT	PT2A900S.TIF	FIG4_1.WP6
4.2	PIPE2.DZT	P2A900S1.TIF	FIG4_2.WP6
4.3	PIPE2.DZT	P2A900S2.TIF	FIG4_3.WP6
4.4	PIPE2.DZT	P2A900S3.TIF	FIG4_4.WP6
4.5	PIT2A.DZT	PIT2A3_2.TIF	FIG4_5.WP6
4.6	2A2.DZT	PIT2BC.TIF	FIG4_6.WP6
4.8	PIT2A.DZT	CR.TIF	FIG4_8.WP6
4.9	2A2.DZT	NOCR.TIF	FIG4_9.WP6
4.10	PIT1A2.DZT	PIT1A2_2.TIF	FIG4_10.WP6
4.11	1A2N.DZT	WATER.TIF	FIG4_11.WP6
4.12	3B1.DZT	CHANGE.TIF	FIG4_12.WP6
4.13	3B1.DZT	SSBR.TIF	FIG4_13.WP6

Survey Data

Figure	Raw Data	SURFER File	Wordperfect File
3.11	PLT1MB.WKS	PLOT13D.SRF	FIG3_11.WP6
3.12	PLT2MB.WKS	PLOT23D.SRF	FIG3_12.WP6
3.13	PLT3MB.WKS	PLOT33D.SRF	FIG3_13.WP6
3.14	PLT1MB.WKS	PLT1PIT.SRF	FIG4_14.WP6
3.15	PLT2MB.WKS	PLT2PIT.SRF	FIG3_15.WP6
3.16	PLT3MB.WKS	PLT3PIT.SRF	FIG3_16.WP6
3.17	P1WTR.WKS	P1WTR.SRF	FIG3_17.WP6
3.18	PLT2MB.WKS	PLOT2A.SRF	FIG3_18.WP6
4.7	PLT2MB.WKS	P2SD.SRF	FIG4_7.WP6

VITA

James Carter Hamlett was born in Nashville, Tennessee on November 16, 1971. He attended Lawrence County High School and was graduated in May 1990. He entered Tennessee Technological University in August 1990 and received a Bachelor of Science degree in Agriculture with a concentration in Agriculture Engineering Technology in May 1994. He was hired as a Graduate Research Assistant in June 1994 and initiated study toward the Master of Science degree in Agriculture Engineering Technology. Upon completion of the Masters program, he began working for John Deere Company.

#3
mg