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I am submitting herewith a thesis written by Lester Leroy Leonard entitled "Mobile Field Systems for Rapid Subsurface Data Acquisition Using Electromagnetic Induction and Ground-penetrating Radar." I have examined the final paper 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 Biosystems Engineering Technology.

Dr. Robert S. Freeland, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Vice Provost and
Dean of Graduate Studies

Mobile Field Systems for Rapid Subsurface Data Acquisition Using Electromagnetic Induction and Ground-penetrating Radar

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Lester Leroy Leonard
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DEDICATION

This thesis is dedicated to my mother, Mary Ann Leonard, and my father, David William Leonard whose wisdom, teaching, support, and love have guided me throughout my life. Appreciation is extended to my girlfriend, Julie Marshall, whose love and understanding were crucial to my success in graduate school. A special thanks is extended to my kayaking comrades who made the days off from school relaxing.

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ABSTRACT

With increasing technological advances in subsurface surveying and geographical positioning, the ability to efficiently and accurately produce maps of subsurface features is a reality. The use of technological equipment is expensive, but surveying costs can be reduced by enhancing the advantages and utility of the equipment. In particular, technological advances in geophysical equipment are leading to efficient protocols in subsurface data acquisition. In order to effectively map and analyze data, especially in a geographically referenced environment, exact geographical positions of sample data must be obtained. With the widespread availability and dropping costs of differential global positioning systems (DGPS), commercial and institutional fields alike are turning to this surface surveying technology for a variety of applications. Coupling geophysical instrumentation with DGPS technology extends the limits of subsurface surveying accuracy and efficiency.

When compared to traditional intrusive techniques like soil-core analysis and well monitoring networks, geophysical instrumentation, especially non-intrusive instrumentation, has the ability to collect more samples, over the same area, and in the same amount of time. Increasing the efficiency of geophysical surveying with mobility and maintaining data integrity yields accurate results and better management decisions. Preservation of existing environmental conditions is inherent to non-intrusive geophysical surveys. This is especially important for cases in which temporal observations have to be made on the same landscape and repeated ground disturbances could affect natural processes like groundwater flow. One disadvantage inherent to geophysical equipment is the introduction of error caused by interference from a variety of sources, both natural and anthropogenic.

Focusing on the advantages of non-intrusive geophysical surveying, this study provides a description and analysis for the utility of two mobile survey systems utilizing electromagnetic induction (EMI) and ground-penetrating radar (GPR). Mobility of both systems was possible with the use of an all-terrain utility vehicle. The vehicle was used to tow an instrument cart while operating the mobile EMI survey system and an antenna skid while operating the mobile GPR survey system. The objective of this study was to provide increased survey area coverage using EMI and GPR with no loss in survey accuracy. Interference and efficiency studies were conducted on the mobile EMI survey system and the mobile GPR survey system. Results of these tests indicate nominal interference from the system components. Efficiency studies were also conducted on both survey systems. These tests indicate that both systems are highly effective for rapidly acquiring geographically referenced subsurface feature data. In fact, data show that the mobile EMI survey system is 100 times faster than a traditional manual survey and the mobile GPR survey system reduced data-acquisition and post-processing times by half. The final product in both systems is the ability to produce subsurface feature maps in a GIS environment. For both systems, the final mapping utilizing data from the mobile survey system was found to be more efficient than mapping with data acquired using traditional techniques. In fact, data from this study suggest the mobile GPR survey method is 400% more efficient in GIS integration and mapping.

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LIST OF ABBREVIATIONS

ATV	All-terrain Vehicle
cc	Cubic Centimeter(s)
cm	Centimeter(s)
DGPS	Differential Global Positioning System
EMI	Electromagnetic Induction
ESRI	Environmental Systems Research Institute, Inc.
GIS	Geographical Information System
GPS	Global Positioning System
GPR	Ground-penetrating Radar
GSSI	Geophysical Survey Systems, Inc.
ha	Hectare(s)
hr	Hour(s)
in.	Inch(es)
kg	Kilogram(s)
km	Kilometer(s)
m	Meter(s)
min	Minute(s)
mm	Millimeter(s)
mS	Millisiemen(s)
m^2	Square Meter(s)
N	Newton(s)
ns	Nanosecond(s)
PC	Personal Computer
PVC	Polyvinyl Chloride
r	Coefficient of Correlation
R^2	Coefficient of Determination
SIR	Subsurface Interface Radar

PART I

GENERAL INTRODUCTION

Subsurface exploration, whether discovering the natural features that control subsurface processes or locating anthropogenic objects, is intrinsically important to Earth's societal environment. Everything from subsurface oil exploration and volcanic studies to soil and groundwater research are of great importance to our everyday lives. Many scientific fields are involved with subsurface exploration and utilize a variety of tools for data collection. For example, soil scientists are interested in the physical and chemical properties of soils; soil probing and extracting equipment are used for collection of soil samples. Results from soil scientists, derived from soil investigations, are used for a variety of environmental decisions from precision farming applications to septic tank placement. Another discipline that routinely explores the subsurface is archeology. Archeologists use a variety of tools, including anything from shovels to high-technology geophysical equipment, for insight into a piece of the historical record that is stored in the subsurface.

Often, different disciplines interested in subsurface exploration will collaborate to achieve a common goal by utilizing the specialties and tools from each discipline. For example, archeologists from the Smithsonian Institute are interested in unearthing a particular type of dinosaur for their collection. Knowing that certain dinosaur fossils are found in certain types of soils, archaeologists want to increase the chances for success by digging in area known to contain these dinosaur bones. First, these archeologists might employ geophysicists to survey a large area of land for major soil breaks using geophysical equipment like ground-penetrating radar (GPR). Then, soil scientists might be contracted to further delineate the major breaks into specific soil mapping units. Once the soil units are located, the archaeologists will begin their work by excavating only the areas known to contain the dinosaur bones. This scenario is one example of different geo-exploration disciplines using a spectrum of tools to achieve a common goal.

In the example above, a variety of tools and techniques were used together to pinpoint specific locations of interest saving time and money. Some of these techniques are considered intrusive when removals of physical samples are necessary, whereas other techniques are considered non-intrusive when the data are acquired *in-situ*. As with any environmental analysis, different tools, techniques, and procedures have distinct advantages and disadvantages.

An intrusive subsurface sampling technique, where material from the subsurface is removed or altered, has advantages over non-intrusive techniques. Examples of intrusive sampling techniques include soil-core removal for physical and chemical characterizations, soil-water removal for chemical and flow analysis, or general excavation of objects, whether natural or anthropogenic. The clear advantage of using these techniques is the ability to sample or observe the "true" nature of the sample. For example, GPR, a geophysical tool, has the ability to non-intrusively produce an image of the subsurface. In certain soils, horizons can be distinguished on the radar profile; however, ground-truthing by soil-core analysis is required to fully understand the physical and chemical properties of the soil and to properly calibrate the radar data.

Intrusive sampling is necessary for many subsurface explorations; however, many intrusive sampling techniques have inherent disadvantages. The major disadvantage of intrusive sampling is the possibility of long-term alteration of the medium. Intrusive sampling can alter the sampling area and/or alter the actual sample being taken. For example, bulk density in soils can be determined from a sample of soil taken using a push-probe. In the process of extracting the soil, some of the sample is altered by compression of the soil caused by the frictional interaction between the particles of soil and the surface of the probe. Another disadvantage of intrusive sampling, especially over larger areas, is sample resolution reduction due to time, labor, and material constraints. When tracking a contaminant plume moving through the soil, monitoring wells are often used to gather soil-water samples. There are a finite number of wells that can be installed due to expense and excessive ground disturbance. Since the sampling is limited spatially, a risk exists that the flow of the contaminant will not be detected due to the occurrence of preferential flow between the wells instead of through the wells. Understanding the disadvantages of intrusive sampling has led to the supplementation, or sometimes replacement, of intrusive techniques with non-intrusive techniques, mainly using geophysical instrumentation.

Most non-intrusive subsurface exploration is implemented using geophysical surveying methods. Many, but not all geophysical sampling techniques are non-intrusive. According to Kearey and Brooks (1991), there is a broad spectrum of geophysical equipment that measures the Earth's gravitational, magnetic, electrical, and electromagnetic fields. The techniques used in geophysical surveying include seismic, gravity, magnetic, electrical, electromagnetic, and radar (Kearey and Brooks, 1991). Each of these techniques measures a different physical property. Magnetic methods measure magnetic susceptibility and remanence, while gravitational methods measure medium density. In general, most geophysical data-collection is less time-consuming than intrusive methods; therefore, tighter sampling patterns can be surveyed in the same amount of time.

Often, geophysical data must be calibrated to represent meaningful target data in the subsurface. This calibration requires "truth" data, often collected using intrusive techniques. Therefore, a disadvantage of using most geophysical equipment is the need to have "truth" data and the error that is associated with equipment and data calibration. This error can vary significantly with the equipment being used, the medium being sampled, and the equipment operator. Another disadvantage of some geophysical data is the subjective approach that is taken when making qualitative data interpretations. In some cases, like interpretation of GPR imaging data, trained technicians will draw different conclusions about the same image profile. Most of the time, qualitative geophysical data can be transformed or manipulated into quantitative data that can be used for analysis without misinterpretation or bias. Site constraints can also be a disadvantage to using geophysical equipment. Depending on the instrument used, geophysical data can be distorted by a variety of anthropogenic sources including electrical and magnetic fields generated from above- or below-ground electrical lines, lightning storms, buried metal objects, piping, or other ground disturbances. In addition, some geophysical instrumentation is sensitive to tree coverage, and therefore cannot be used in a forest. Other equipment is pulled across surfaces where smooth terrain is sometimes necessary to prevent the introduction of excessive noise. Properly interpreting geophysical data involves an understanding that error is caused by noise. Once noise is managed, reduced and/or eliminated, geophysical data interpretations become more reliable.

Subsurface exploration using geophysical equipment has many advantages when compared to other sampling methods. The greatest advantage, especially for non-intrusive, geophysical instrumentation, is the ability to gather data without significantly altering the natural processes of the subsurface area of interest. This is extremely important when tracking temporal changes within a subsurface system because repeated samples can be taken on the same area, over time, with confidence that the data are not distorted due to a previous ground disturbance. Another advantage inherent to some geophysical equipment is the ability to cover larger areas, with increased sampling resolution, and in less time than compared to intrusive techniques. This advantage provides greater confidence in data accuracy, thereby providing greater confidence in conclusions. Given the ability to cover larger areas, some geophysical equipment is well suited for rapid reconnaissance of an area prior to more expensive, intrusive testing. For example, seismic methods are often used to determine geological boundaries in the exploration of oil. Once these boundaries and depths are located, drill rigs are directed to these locations, and drilling begins with increased confidence for success.

Focusing on the ability of non-intrusive geophysical instrumentation to cover larger areas due to increased sampling rates, this thesis provides a description of two mobile survey systems, utilizing different, non-intrusive geophysical equipment. The purpose of this study was to substantially increase the rate of subsurface data acquisition without affecting accuracy. Data resolution enhancement, resulting from larger sample numbers and tighter sampling patterns, provides greater confidence in accuracy. Both mobile survey systems were integrated with a differential global positioning system (DGPS) for accurate geographical positioning. The first system, described in Part II, was developed to provide mobility to an electromagnetic induction (EMI) instrument, while the second mobile survey system, described in Part III, was designed to increase ground surface coverage with a GPR unit. Both systems require an all-terrain utility vehicle for transport across a landscape. General operating principles and survey procedures for these geophysical tools, as well as integration of spatial sampling into a geographical database, are described below.

With technological advances, soil electrical conductivity can now be measured non-intrusively with an EMI instrument. Today's non-intrusive EMI instrumentation is combined in one unit consisting of a transmitter, receiver, and processor. For automated data-collection, a data-logger is also required. Electrical conductivity is measured as the transmitter induces circular eddy current loops into the soil. Under certain conditions, controlled by internal programming, the magnitude of any one of these loops is directly proportional to the conductivity in close proximity to that loop. Part of the magnetic field from each loop is received as an output voltage and is linearly related to soil conductivity (Geonics Ltd., 1995).

The apparent electrical conductivity of soils has been used to indirectly measure a variety of soil properties including salinity, moisture content, topsoil depth, and clay content (Sudduth *et al.*, 2001). Specific examples of EMI investigations include estimation of depth to claypans (Doolittle *et al.*, 1994), estimation of herbicide partition coefficients (Jaynes *et al.*, 1995), monitoring for temporal changes in soil salinity (Lesch et al., 1998), and usage as an aid for soils mapping in precision farming (Jaynes, 1995). The traditional survey protocol for most non-intrusive EMI instrumentation requires a technician to manually gather data at discrete points. If geographical positioning is required, the technician revisits the EMI sample points with a GPS unit or other survey device.

Continuous subsurface imaging is possible with the use of GPR. Non-intrusive GPR systems consist of a mainframe, an antenna (transmitter and receiver), and a recording device. Ground-penetrating radar systems transmit and receive pulse radio frequencies from the transmitter, through the ground, until the pulses hit an interface with differing dielectric properties. At these interfaces, some of the energy continues downward to the next interface, while some is reflected back to the receiver. The mainframe processes the intensities of the returned energy, and the recording device logs the data for further investigation (The Finnish Geotechnical Society, 1992).

Data from GPR imaging can provide detailed information about subsurface conditions. Varieties of studies have been conducted with GPR. Examples include use of GPR to map bedrock profiles (Birkhead *et al.*, 1996) to increase the efficiency and resolution of soil surveys (Doolittle, 1987), to determine soil water content (Chanzy *et al.*, 1996), and to measure water table fluctuations in sandy soils (Smith *et al.*, 1992).

Traditional GPR survey protocols require the use of two or more operators to conduct a survey. Generally, the mainframe remains stationary while an operator pulls the antenna across a surface of interest. As the operator places location points in the GPR scan file, a second operator monitors the progress and calibration of the GPR scan from the mainframe display monitor. Using this technique, surface area coverage is limited by the length of the control cable.

With the use of DGPS geographical positioning, integration of subsurface feature data into a geographical information system (GIS) database is possible. Integration of subsurface feature data requires assigning locations to each sample. These samples can be apparent soil conductivity values collected with an EMI instrument or interpreted depths-to-bedrock from a GPR scan. Once the data have been integrated, high-resolution maps of interpreted subsurface features can be generated. These maps can be used as overlays with other field features, creating a database for future management decisions. With the ability to efficiently and accurately gather positional data and integrate geographical locations with geophysical sample data, survey expense can be decreased with increasing confidence in data accuracy.

The mobile survey systems described in this document were designed to facilitate efficient and accurate subsurface data acquisition, thus reducing time and labor costs. One disadvantage of many geophysical tools is the expense due to the costly nature of geophysical instrumentation and the need for technically trained labor. This expense often outweighs the utility of geophysical equipment for many applications; therefore, the use of such instrumentation is not widespread. By significantly increasing the sampling rate and reducing labor, the expense of using geophysical equipment decreases. With the use of GPS and GIS, survey expense can further be reduced.

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PART II

MOBILIZED SURVEYING OF SOIL CONDUCTIVITY USING ELECTROMAGNETIC INDUCTION

INTRODUCTION

Soil surveyors routinely rely upon visual extrapolations of aboveground terrain to predict subsurface features. However, precision soil mapping requires verification beyond subjective aboveground observations. In order to produce an accurate and precise survey, intensive borehole sampling must be conducted. This type of survey is both labor-intensive and site-invasive. The intrusive sampling process itself may significantly alter the physical properties of both site and sample. For example, soil borings distort the soil structure of the extracted sample core, altering its bulk density. Due to the expense of obtaining additional physical samples on closely spaced grids, and to site constraints against destructive sampling, highly precise conventional soil surveys are not always feasible.

One method of supplying high-resolution, non-destructive surveys is employing one of several near-surface geophysical sensing instruments, two of which are ground-penetrating radar (GPR) and electromagnetic induction (EMI). Both technologies can precisely highlight boundaries that separate differing soil electrical characteristics, and may potentially supply greater insight into the dynamic features of the subsurface, such as moisture migration paths and contaminate flow.

Whereas GPR generates a pseudo-image of the subsurface that requires highly trained interpretation, EMI generates a bulk-volume conductivity value for each given locale. Both technologies, which can be supplemented with ground-truth data, provide a significant reduction in site surveying time over site-invasive surveys, while supplying greatly increased mapping resolution and precision.

Many researchers have reported on the increased efficiency of using EMI for a variety of subsurface surveys. Sheets and Hendrickx (1995) reported that the relationship between total soil water content, determined by a neutron probe, and the electrical conductivity of an arid New Mexico soil could be explained by simple linear relationships with coefficient of determination (R^2) values ranging from 0.58 to 0.64. Sheets and Hendrickx (1995) also found that EMI instruments have tremendous advantages due to their speed and ease of use, and further stated that their transect took 40 min to survey with the EMI meter compared to almost a day with the neutron probe. Jaynes *et al.* (1995) conducted an experiment to see if herbicide partition coefficients could be estimated from electromagnetic induction measurements on soils in central Iowa. They found that conductivity measurements provided reasonable estimates of the partition coefficient for atrazine, and they further stated the real advantage to non-intrusive conductivity measurements is the speed and ease of operation in taking multiple samples over a large area. Bork *et al.* (1998) showed that EMI could efficiently map soil depth to bedrock, and could be correlated to rangeland site quality in assessing grazing treatments. They reported that EMI offers a rapid, non-invasive, and efficient tool for quantifying and mapping soil depth. In addition, the EMI process did not require intensive ground truthing—a time-consuming task. In similar studies, Doolittle and Collins (1998) stated that bedrock depths on a Pennsylvania site could be estimated using EMI, based on depth classes. Doolittle *et al.* (1994) also found that claypan depths of Mexico (fine, montmorillonitic, mesic Udollic Ochraqualfs) soils in Missouri could be determined using the apparent conductivity obtained from a non-intrusive conductivity meter, stating that a large number of EMI samples could be collected in a short period of time. Ammons *et al.* (1989) reported that a non-intrusive conductivity meter proved to be a rapid and accurate method for delineating two soil taxa, Natraqualfs and Ochraqualfs, based on soil salinity.

Survey Protocols

Carrying the EMI instrument while walking over a site has been the predominant method of surveying among practitioners, both researchers and survey contractors. The specific protocol used has been multi-faceted, site dependent, and has often varied among individual surveyors. Commonly, manual surveys require a technician walking over the site carrying the instrumentation, positioning the instrument over a point, and triggering data acquisition (fig. 2.1). Data are later downloaded to a computer for analysis and mapping. The instrument is positioned using an established grid of survey flags, which have coordinates that are pre- or post-surveyed using a GPS recorder or standard surveying equipment (fig. 2.2). Using survey flags require the additional time-consuming steps of marking and placing the flags, and later manually merging conductivity and position coordinate data.

A second method involves the simultaneous triggering of a GPS recorder along with the time-synchronized EMI data logger, and later merging the data within the EMI and GPS files via common time stamps. However, the additional instrumentation operation and weight makes this method both highly cumbersome and physically strenuous. To address this drawback, various systems have been developed for supplying powered mobility across a survey site. Often vehicles are selected solely on availability and convenience. Vehicles commonly used are small four-wheel all-terrain vehicles (ATVs), utility vehicles, garden tractors, agricultural tractors, and pick-up trucks.

In a soil salinity mapping study by Cannon *et al.* (1994), researchers used a non-magnetic toboggan, which was towed behind an ATV, to carry an EM38 conductivity meter (Geonics, Ltd., Mississauga, Ontario, Canada). A GPS system, mounted on the ATV, was used to position conductivity samples obtained from the EM38. The authors stated that when using the combined EMI/GPS system for field salinity measurements, up to a few hundred hectares per day could be surveyed. Cannon *et al.* (1994) also concluded that productivity was increased by a factor of five compared to the use of grid EMI survey methods. In another study conducted by Kitchen *et al.* (1996), sand deposition from the 1993 Midwest floods was successfully mapped by use of a trailer designed to carry an EM38 conductivity meter behind an ATV. A GPS unit was mounted on the ATV, and location data were post-processed and assigned to corresponding conductivity data.

In-house attempts to adapt previous designs for a vehicle-mounted EM31-MK2 (Geonics, Ltd., Mississauga, Ontario, Canada) conductivity meter were unsuccessful. These designs included front- and rear-mounted instruments attached directly (or in near proximity) to the utility vehicle perpendicular to the direction of travel. Calibration tests revealed significantly altered conductivity measurements, an influence caused by the near-proximity of the metallic chassis and ignition electrical noise.

Objectives

The objectives of this project were to:

1. Design and evaluate a mobile EMI survey system that did not significantly alter ground conductivity measurements from those obtained using the conventional manual survey method, and
2. Compare differences in data acquisition speed and survey resolution between the design efficacy of mobile survey system to two different manual survey protocols.

MATERIALS AND METHODS

Equipment used in this project included: 1) a non-intrusive conductivity meter, 2) an in-house designed carriage as a towed field carrier for the conductivity meter, 3) an all-terrain utility vehicle for powered transport, and 4) a GPS system for real-time positional data. Studies were conducted on the loessial soils of southwest Tennessee using three types of data collection protocols—two manual survey methods (with and without simultaneous GPS time stamps) and the Mobile Survey Method with GPS time stamps.

EM31-MK2 Conductivity Meter

The EMI instrument used in this project was the EM31-MK2. This instrument detects near-surface geological variations, groundwater contaminants, or any subsurface features that affect changes in ground conductivity. A patented electromagnetic inductive technique allows measurements without electrodes or ground contact (Geonics, Ltd., 1995). The instrument has the ability to measure bulk soil conductivity to a depth of approximately 6 m. If rotated 90^{o} along the longitudinal axis, the conductivity meter measures bulk soil conductivity to a depth of approximately 3 m (Geonics, Ltd., 1995). When assembled, the instrument is 4 m long. Two cylinders, one a transmitting antenna and the other a receiving antenna, are fastened in-line to a center control console that has an incorporated data logger.

Instrument Carriage

An in-house designed instrument carriage was developed to transport the conductivity meter across the survey site. The design concept was based upon a similar instrument carrier design of Geonics Ltd. of Mississauga, Ontario, Canada. To minimize ambient conductivity interference, the carriage was constructed of non-metallic components, mainly extruded, structural, fiberglass components. The conductivity meter was oriented and secured in a parallel fashion along the center axis of the carriage, which in turn was towed behind the ATV. A GPS antenna was positioned in close proximity to the conductivity meter's center console, and the GPS antenna cable was secured alongside the carriage. The GPS receiver was fastened near the operator to monitor GPS data quality (fig. 2.3).

The carriage cradled the EMI instrument using four PVC mounts. Foam rubber blocks within the mounts supported the instrument, provided shock absorption, and reduced the bending moment along the instrument's longitudinal axis whenever the carriage frame flexed during field surveys traversing uneven terrain. The carriage frame was a single, 8-in. fiberglass I-beam, 7.5 m long, segmented into four smaller lengths for breakdown, transportation, and storage. During field assembly, the four inline I-beam segments were joined by fiberglass plates, bolts, and nuts, which were bolted to the wheel chassis. In turn, the fiberglass wheel chassis had fixed axles and tandem plastic-spoke wheels that supported the carriage frame.

Design tests were conducted to determine the offset length requirement of the carriage from the metallic frame and the engine electrical noise of the utility vehicle. From these tests, a fixed surface reference point was selected, and conductivity was measured in the traditional hand-held manner. With the instrument at a fixed position, the vehicle was reversed by 0.15-m increments until the influence of the vehicle was detected by conductivity readings. Overall, three tests were conducted to determine the best distance and orientation for the conductivity instrument. First, the transmitter coil was oriented towards the utility vehicle. Next, the receiver coil was positioned towards the utility vehicle. Finally, both coils were oriented perpendicular to the vehicle travel direction. The offset length of the carriage from the utility vehicle was selected to be 5.6 m (fig. 2.4), which will vary based upon the type of vehicle employed to tow the carriage. The receiver positioned toward the rear of the utility vehicle proved to be the preferred position with the least interference recorded.

All-Terrain Utility Vehicle

This project used a Kawasaki Mule Model 2510, a four-wheel drive utility vehicle that has a four-stroke, 617-cc displacement gasoline engine with electronic ignition. The

Model 2510 has a 2.85-m overall length, a 0.17-m ground clearance, a 3.41-m turning radius, and 5338-N towing capacity.

Global Positioning System

Geographical position of each survey locale was obtained using an AgGPS 132™ (Trimble Navigation Limited, Sunnydale, CA, USA). Used with real-time, differential correction data, this GPS unit measured geographical location with sub-meter resolution (< 0.75 m). The GPS receiver transmitted continuous real-time, differentially corrected, geographical coordinates, which were recorded using a palmtop computer. Data obtained from this unit provided precise time-stamped positional coordinates for presentation in ArcView GIS 3.2 (Environmental Systems Research Institute, Inc., Redlands, CA).

Research Site

The site was located at N35°8'5",W89°13'41", on an upland position, with a site elevation that was 164 m above mean sea level. The parent material sequence was loess over alluvium over Tertiary-aged sands. The research site contained several agricultural production fields lying within the same watershed. An approximate 1-ha grass field, with slightly varying topography, was selected for survey method comparisons.

Survey Methodology

The Mobile Survey Method efficacy was compared against two manual survey protocols: 1) a Manual Survey Method using GPS time stamps, and 2) a Conventional Manual Survey Method employing pre-positioned survey flags. From previous experience, tasks were first separated into fixed and variable times. Fixed times were recorded for tasks that did not vary for collecting one sample point or a 1000 sample points. Variable times were recorded for tasks that varied depending on number of sample points. For each of the three survey methods, fixed and variable times were recorded and documented from field trials (Tables 2.1 and 2.2).

A 1-ha open field was selected, having 1200 data points spaced at 3 m, an interval approximating automated sampling rate at average vehicle speed. A smaller 6 m x 66 m subset of this field was selected for the Manual Survey Methods, and data were extrapolated to represent the entire 1-ha field. For determining data quality, five points at various sites were surveyed with the EMI instrument held manually, and with the instrument mounted on the carriage.

Mobile Survey Method

A utility vehicle carried the operator and equipment across the field, while towing the instrument carriage (fig. 2.3). Two autonomous data collection systems, the EMI data logger and a GPS palm top computer, collected continuous data streams of 1) time-stamped soil conductivity data, and 2) time-stamped GPS data. After traversing the survey site, both data sets were automatically merged using the time stamp data as an indexer. Using GIS, high-resolution conductivity maps were produced onsite. Other than normal breaks, the operator worked continuously, requiring little or no rest intervals.

Manual Survey Method – Conventional

Survey flags were numbered, and placed based on the sampling pattern. Flag locales were recorded by positioning a GPS receiver briefly above each flagged position (fig. 2.2). Flag locations were revisited with the EMI instrument, and conductivity readings were logged (fig. 2.1). Post-processing of data required manually assigning GPS coordinates to conductivity values based on flag numbers, and incorporating this data into a GIS database prior to map generation. Occasional rest breaks were needed during the survey due to the weight and awkwardness of the equipment.

Manual Survey Method –GPS time stamp

An operator carried both the GPS and EMI equipment across the field. As with the mobile method, two autonomous data collection systems collected continuous data streams of time-stamped soil conductivity data and time-stamped GPS data. After walking the survey site, both data sets were automatically merged using the time stamp data as an indexer. Using GIS, high-resolution conductivity maps were produced onsite. The operator could not physically sustain conducting the survey continuously, requiring rest intervals due to the cumbersome and strenuous working condition.

RESULTS AND DISCUSSION

Data Acquisition Speeds

For this site and conditions, recorded fixed and variable task times (Tables 2.1 and 2.2) provided general estimates that may be applied to other sites and conditions. Data and derived equations developed from this study are empirical, and are based upon a single operator's experience. However, the data and derived equations reflect general comparison results among the survey methodologies.

For this study, the Mobile Survey Method had the greatest fixed time, approximately double that of the two manual surveys. This is attributable to the additional time for vehicle/carriage setup and storage. The Mobile Survey Method and Manual Survey Method with GPS time stamp had the fastest data collection speeds, with the Mobile Survey Method approximately 100 times faster than the Conventional Manual

Survey Method without GPS time stamp. The additional time for the Conventional Manual Survey Method is attributable to surveying, flag placement, and manual data merging. Results also show that when faced with a survey area requiring more than the threshold value of 23 data points, the Mobile Survey Method should be implemented instead of the Conventional Manual Survey Method (fig. 2.5). Similarly, the Mobile Survey Method should be used instead of the Manual Survey Method with GPS time stamp if the threshold value exceeds approximately 1600 points (fig. 2.6).

The Manual Survey Method using the GPS time stamp was not deemed a viable technique due to the strenuous and cumbersome working conditions placed upon the operator. However, this method will become increasingly viable with technology advances that lead to a reduction in instrumentation mass. Given this scenario, this method may then be preferable for surveying terrains that cannot be traversed readily with a vehicle.

Survey Resolution

Identical survey resolution can be achieved using the Mobile Survey Method and the Conventional Manual Survey Method. The Mobile Survey Method does have increased resolution when time restrictions are integrated into the comparison. A dramatic increase in survey resolution was noted by researchers, using the Mobile Survey Method, given one eight-hour workday day to collect data using both of the survey methods.

The 1-ha site was surveyed using the Conventional Manual Survey Method, which generated 150 points and required 230 min on-site plus 350 min off-site for completion of a GIS plot (fig. 2.7). Sampling points were selected based upon an approximate 10 m x 10 m sample interval and major terrain breaks. The site was then surveyed using the Mobile Survey Method, which generated 1947 points while traversing the site (one-hr driving). Including fixed times, the Mobile Survey Method took a total of 220 min to completion of a GIS conductivity map (fig. 2.8). Some points overlapped while traversing the site with the vehicle.

Overall, the Mobile Survey Method provided a conductivity map with approximately 10 times the resolution of a similar map produced from the Conventional Manual Survey. The same survey resolution could have been obtained using the Conventional Manual Survey, however, the time required to complete the survey would have theoretically exceeded 8.5 eight-hour workdays.

Data Quality

Mobile survey interference tests were completed along a single transect in a fallow, agricultural field at Ames Plantation. Data were collected, using both the mobile and manual survey techniques, at 10 sample points, spaced 5 m apart. Conductivity data were acquired at two depths using both survey methods. High correlation (r) values (Table 2.3) indicate a strong relationship between conductivity values obtained using the two survey techniques. While there appeared to be little interference from the utility vehicle, the fiberglass trailer itself affected the relative conductivity values obtained using the mobile survey technique. Linear equations (Table 2.3) were derived to calibrate the values obtained using the mobile technique at both depths. However, when mapping conductivity trends and boundaries in subsurface features, it is not necessary to calibrate the relative conductivity values obtained using the mobile technique.

SUMMARY AND CONCLUSIONS

A non-invasive soil surveying system was developed to rapidly map soil characteristics. This system employed an all-terrain utility vehicle towing a nonmetallic carriage, which cradles a commercially available ground conductivity meter. Autonomous data streams of 1) time-stamped soil conductivity data and 2) time-stamped global positioning system (GPS) data were immediately downloaded to a PC after the survey. Both data sets were automatically merged together using the time stamp data as an index. Using geographical information software (GIS), high-resolution conductivity maps were produced onsite.

This mobile survey method increased the total conductivity sampling rate by a factor of >100, and increased data resolution by a factor of >10 over a conventional manual survey method. For open fields that can be easily traversed with a utility vehicle, the mobile surveying system was found to greatly enhance data quality by increased resolution, and to dramatically increase both data acquisition efficiency and data post-processing speeds.

Results of this study indicate that survey method decisions, in practical applications, can be made based on threshold values. For example, if a survey is to be conducted, with a 3 m sampling grid, the Mobile Survey Method should be used instead of the Conventional Manual Survey if the study area exceeds approximately 60 m^2.

Similarly, the Manual Survey Method with GPS time stamp is preferred over the Mobile Survey Method if the survey area is less than approximately 1.4 ha.

Data quality tests designed to evaluate the interference of the mobile carriage and the utility vehicle indicated little interference when compared to the same data collected using the Conventional Manual Technique. Mobile field system conductivity data do not need to be calibrated when distinguishing major breaks in conductivity boundaries over a given area. However, simple linear equations, with high R^2 values, have been derived to calculate absolute conductivity values from mobile survey conductivity data.

The Manual Survey Method using the GPS time stamp is not a viable technique for larger survey areas due to the strenuous and cumbersome working conditions placed upon the operator. However, this manual method will become increasingly viable with technology advances that lead to a reduction in instrumentation mass, and for surveying terrains not vehicle accessible.

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PART II APPENDIX

Table 2.1. Fixed times—for setup, calibration, storage, data-processing, and GIS integration

Manual Survey (Conventional)	Time (min)	Manual Survey (GPS time stamp)	Time (min)	Mobile Survey (GPS time stamp)	Time (min)
Plot survey (field observation)	10	Plot survey (field observation)	10	Plot survey (field observation)	10
EM31/GPS setup, calibration, and storage	23	EM31/GPS setup, calibration, and storage	23	EM31/GPS setup, calibration, and storage	23
Data download	22	Data download	22	Data download	22
Spreadsheet compilation	8	Spreadsheet compilation	8	Spreadsheet compilation	8
GIS integration	12	GIS integration	12	GIS integration	12
		Merging GPS and EMI data	2	Merging GPS and EMI data	2
				ATV/Carriage setup, storage	75
TOTALS	75		77		152

Table 2.2. Variable times—per 1200 data points @ 3-m spacing (~1 ha)*

Manual Survey (Conventional)	Time (min)	Manual Survey (GPS time stamp)	Time (min)	Mobile Survey (GPS time stamp)	Time (min)
Flag labeling	209	EMI/GPS data collection	77	EMI/GPS data collection	40
Flag placement[†]	296				
GPS data acquisition	800				
EMI data acquisition	557				
Merging GPS data/EMI data[‡]	1884				
SUBTOTALS	3746		77		40
Break (%) per hour[§]	9%		23%		0%
TOTALS	4087		95		40

* Three-meter grid spacing approximates mobile survey spacing with 2-s sampling rate
[†] Grid node measurements and flag placement and removal
[‡] Averaging GPS points for each point and manually merging GPS data with EMI data
[§] Metabolic rate formula for different work regimes (Kroemer,1988), and metabolic rates for work load categories (ACGIH, 1995)

Table 2.3. Correlation values and calibration equations based on comparisons between mobile and manual conductivity values

Depth	r	Calibration Equation	R^2
6 m	0.96	$y = 0.90x - 0.86$	0.93
3 m	0.90	$y = 1.25x - 2.72$	0.82

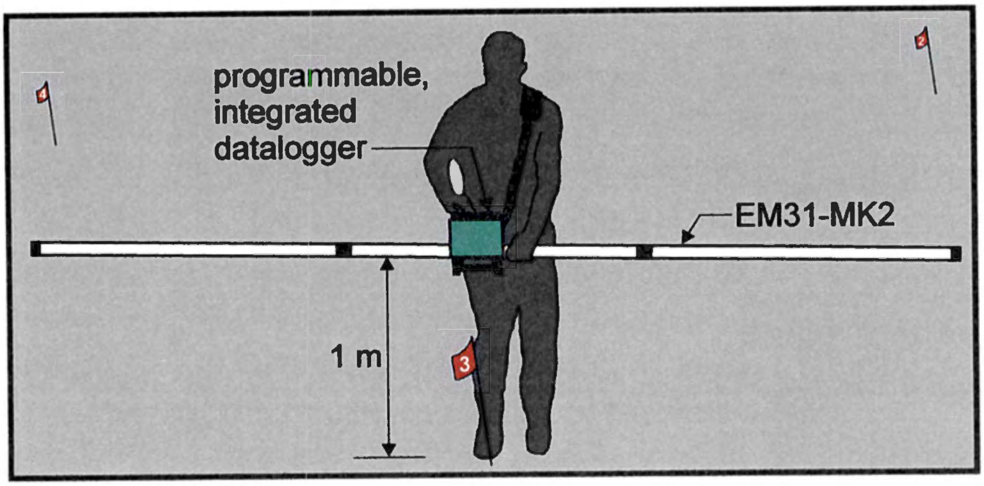

Figure 2.1. Conventional EMI survey with instrument directly above sample point, and operator triggering data acquisition

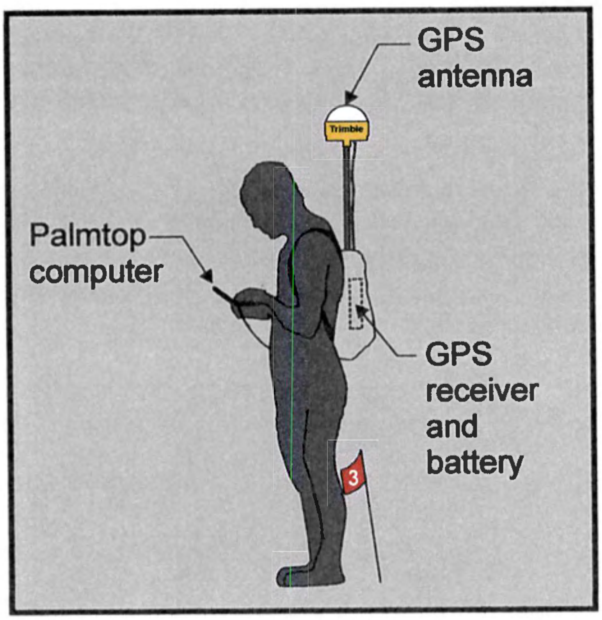

Figure 2.2. Geographically positioning EMI sample points for analysis of conductivity values in a GIS environment

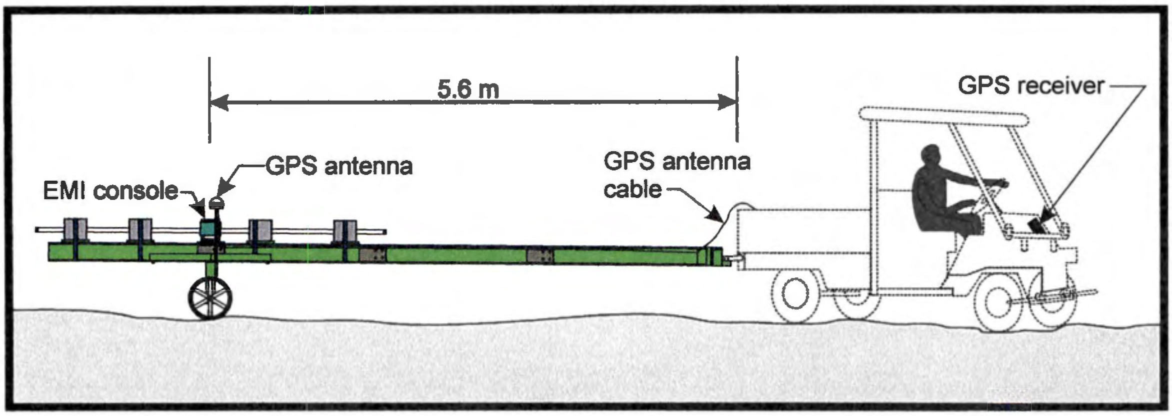

Figure 2.3. Mobile Survey System and GPS components: antenna positioned over EMI console, antenna cable suspended alongside carriage body, and GPS receiver

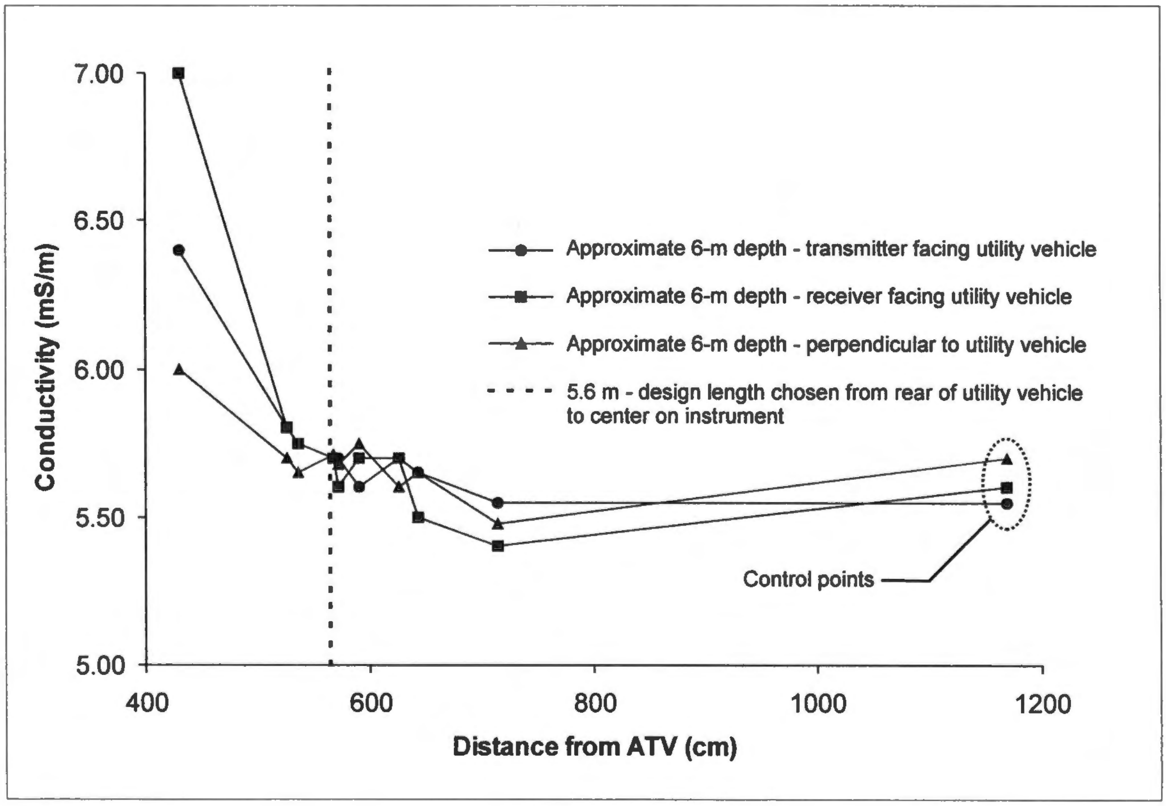

Figure 2.4. Distortion of constant conductivity values (control points) due to influence of the metallic frame and the engine electrical noise of the utility vehicle as a function of separation distance

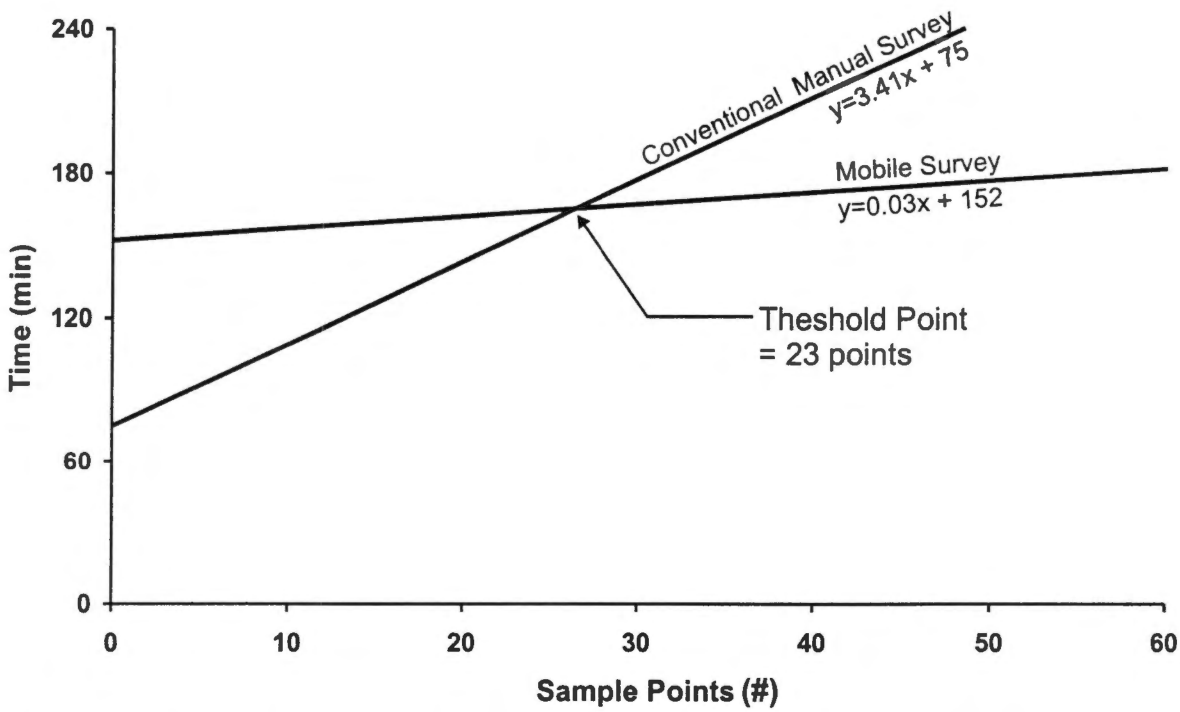

Figure 2.5. Conventional Manual Method and Mobile Method survey times as a function of sample points

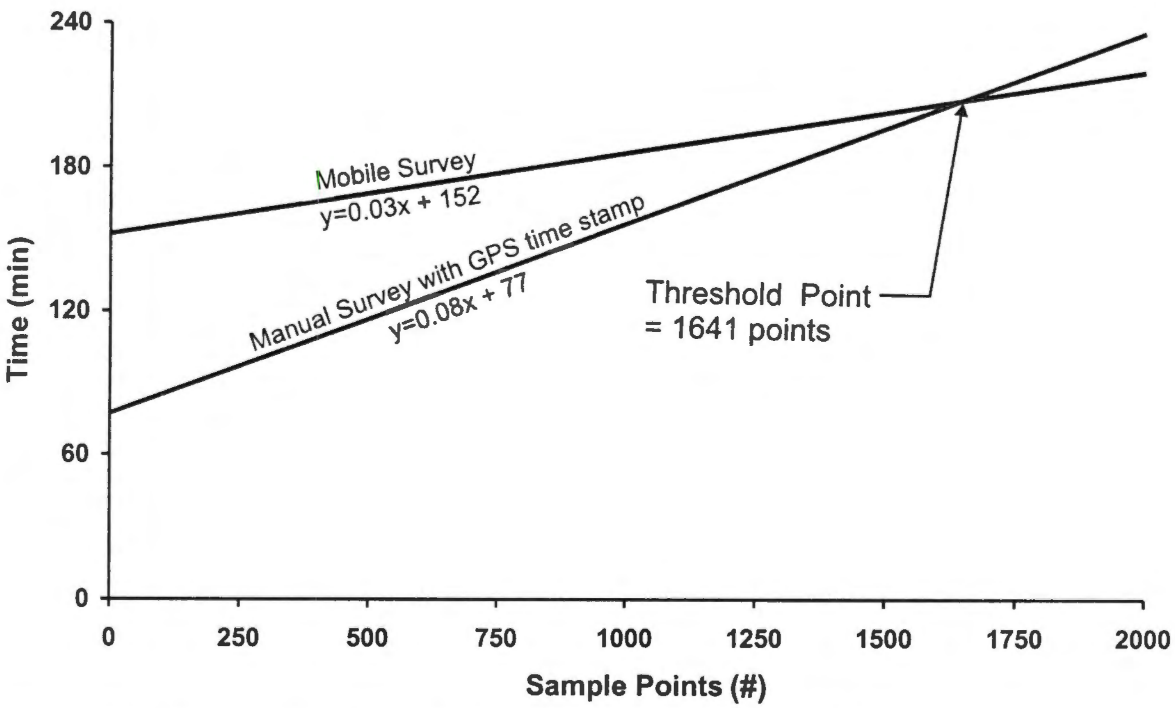

Figure 2.6. Manual Method with GPS time stamp and Mobile Method survey times as a function of sample points

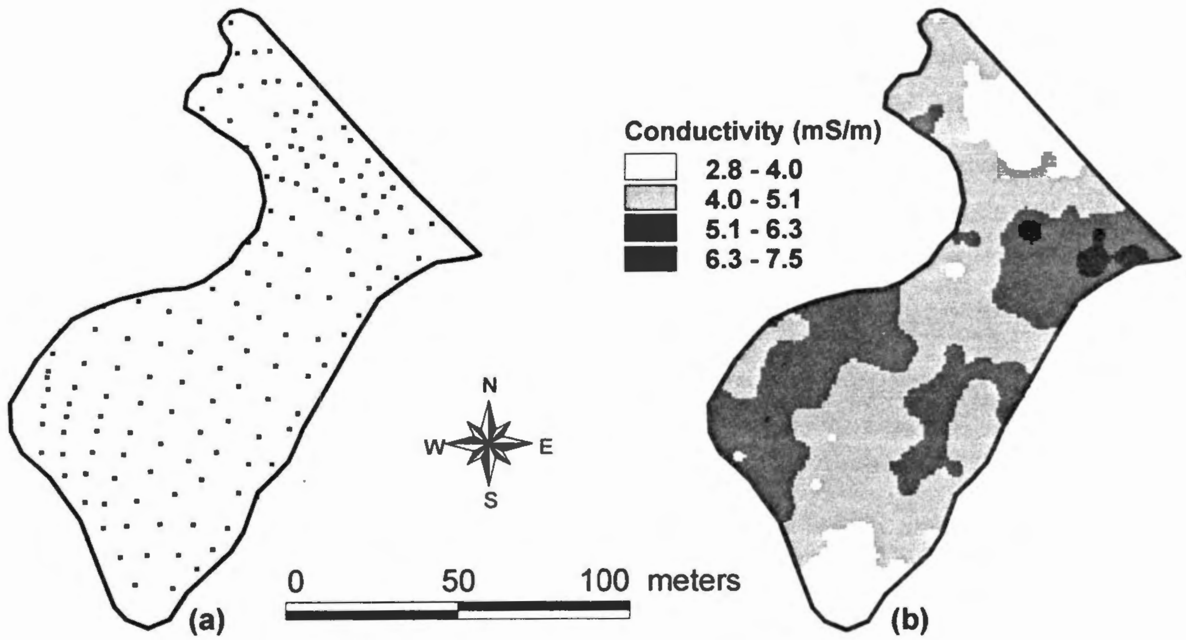

Figure 2.7. (a) EMI sample points acquired using the Conventional Manual Method (150 points/ha), and (b) resultant low-resolution conductivity map during moist soil conditions requiring 580 min to map completion

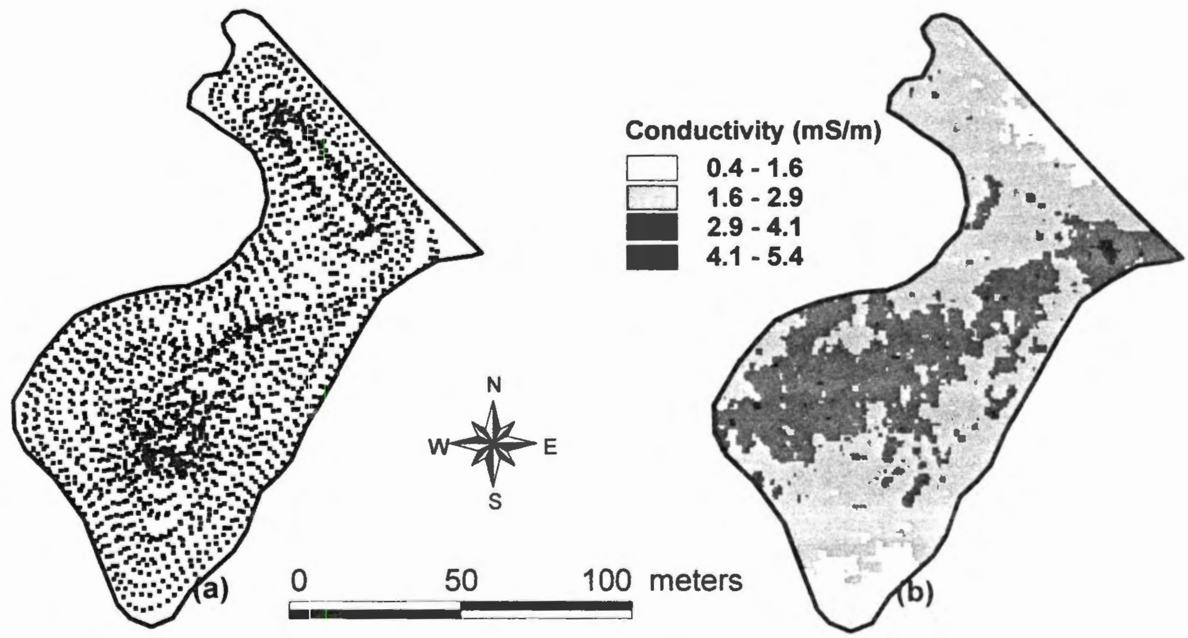

Figure 2.8. (a) EMI sample points acquired using the Mobile Method (1947 points/ha with some overlap), and (b) resultant high-resolution conductivity map during dry soil conditions requiring 220 min to map completion

PART III

MOBILE FIELD SYSTEMS FOR RAPID SUBSURFACE SURVEYING USING GROUND-PENETRATING RADAR

INTRODUCTION

Ground-penetrating radar (GPR) is a geophysical technique that supplies continuous imaging profiles of layered and object-embedded earthen material. This technology provides the distinct advantage of continuous, non-invasive soil profiling; revealing features that discrete sampling methods may misrepresent or fail to detect. Ground-penetrating radar performs best on dry and coarse soils, with decreasing performance as moisture, salinity, or soil fineness increases. Introductory explanations of the basic, governing principles and abilities of GPR systems are described by The Finnish Geotechnical Society (1992).

Many researchers have reported on the success of continuous profiling of subsurface features using GPR. For example, Hubbard *et al.* (1990) in their soils investigation concluded that GPR provides clear, continuous delineation of subsurface features on the sandy upland soils of the Georgia Coastal Plain. These authors further stated that GPR provided continuous records of soil horizons, water tables, and geologic layers. In another study, Truman *et al.* (1988) found that GPR could detect the depth and spatial variability of argillic soil horizons and water tables.

Numerous GPR system configurations exist and are largely marketed for non-agricultural applications where manual towing, pushing, or carrying the system (radar unit, power supply, and antenna) is effective. As the antenna moves across the site, numeric markers are inserted by the operator within the image whenever the antenna coincides with pre-surveyed or fixed reference points. This allows position referencing within the image at precise locales. Survey flags or other markings must be accurately placed on a precise grid throughout the course before subsurface surveying can commence. Therefore, when using a manual marker method, surveying larger land tracts with GPR becomes increasingly constrained due to course layout requirements, physical exertion, and labor costs.

Realizing these limitations, agricultural scientists have developed specialized mobile platforms to transport the GPR antenna, system unit, and operators across large agricultural production fields. Truman *et al.* (1988) used GPR to determine selected soil features in the Southern Coastal Plain Region in Georgia. They completed a series of GPR transects with the aid of a tractor towing a trailer that carried both the radar operator and the radar system unit. This trailer, in turn, towed the radar antenna. Vellidis *et al.* (1989) also used a tractor to pull a covered trailer that contained the GPR system and power supply. A skid carried and protected the GPR antenna, as well as mechanically smoothing surface irregularities. Smith *et al.* (1992) used the same technique, a trailer towing a skid, as did van Overmeeren, (1994), who employed an all-terrain vehicle (ATV) to pull a polyethylene carrier. In a related study by Chanzy *et al.* (1996), a crane was used to suspend a radar antenna to determine the viability of airborne GPR in determining soil moisture. Preliminary results indicated potential for mapping soil moisture, with future research directed towards other airborne suspension platforms, possibly using small aircraft to traverse large land tracts in the mapping of soil moisture.

GIS and GPS Integration

With the widespread availability and relatively low cost of geographic information system (GIS) and global positioning system (GPS) packages, indexing GPR images with a GIS database is highly desirable. Integration of data within GIS allows spatial comparisons using variable correlations and overlays of other field parameters. Related research using GIS and GPS technology proves that GIS databases are beneficial to many endeavors where spatial queries exist. For example, Mendonça Santos *et al.* (2000) stated that GIS technology is an undeniable utility for soil scientist mapping soils, especially spatially variable soils. In another study, White and Zasoski (1999) used GIS and GPS technologies to successfully map spatially variable micronutrients in soils providing a GIS management system database for precision agriculture. Referencing any spatially dependent variable requires georeferencing with traditional survey techniques or modern GPS technology.

Although ground-tracking survey wheels are available for some systems that automatically control the placing of image markers, referencing detailed GPR data within a GIS database is time consuming. Converting positioning data referenced by Cartesian coordinates into a GIS database using the Earth Terrestrial Coordinate System (latitude, longitude, and altitude) is an additional, error-prone processing step. When surveying long transects, raw data files often exceed several hundred megabytes. Differential GPS (DGPS) provides real-time transect positioning with sub-meter latitude and longitude positioning accuracy. When interfaced with control software, DGPS can be employed to automatically embed distance markers within the GPR image at predefined travel increments.

Objectives

The objective of this project was to develop, construct, and evaluate a mobile field system for GPR surveying of large land tracts. Specific objectives were to:

1. Develop a mobilized GPR system with no loss in survey accuracy, as compared to traditional GPR surveying,
2. Increase survey efficiency by requiring only a single person as driver and GPR operator, and by incorporating automated DGPS positioning within the survey such that GPR markers are automatically inserted into the GPR data file, and
3. Increase efficiency of GIS database integration and mapping of recorded GPR feature data.

MATERIALS

Major commercial equipment components used in this project included: 1) a GPR unit, 2) a DGPS system for real-time positional data, 3) a GIS package, 4) a laptop computer, and 5) an all-terrain utility vehicle (fig. 3.1). The antenna skid (fig. 3.2) and GPS control and interpolation software (fig. 3.3) were developed in-house.

The GPR system unit used in this project was the SIR System 10A™ (GSSI, Inc., North Salem, NH, USA) which included a 30-m antenna control cable and a 200-MHz antenna (GSSI Model 5106). Geographic position of each survey locale was obtained using a DGPS receiver (AgGPS 132™, Trimble Navigation Limited, Sunnydale, CA, USA). This DGPS unit measured geographical location with sub-meter resolution (< 0.75

m). Using a satellite prescription service (OmniSTAR, Inc., Houston, TX, USA), the GPS receiver processed 1-s data streams of differentially corrected geographical coordinates. Included within the GPS system was an ignition filter (Trimble part no. 36181-00) to eliminate interference from ignition noise from the all-terrain vehicle used in this project, a Kawasaki Mule Model 2510. This four-wheel drive utility vehicle has a four-stroke, 617cc gasoline engine with electronic ignition. The Model 2510 chassis has a 284.5-cm overall length, a 17-cm ground clearance, a 341.4-cm turning radius, and a 5338-N towing capacity.

Antenna Skid

An in-house designed antenna skid (fig. 3.2) was developed to transport a 200-MHz antenna across any survey site having relatively smooth terrain, characteristics common of fields under cultivation. The skid was specifically designed to protect the GPR antenna over long, continuous transect pulls. Fiberglass structural components comprised the frame of the skid and a 6.4-mm PVC sheet was adhered to the underside. The PVC sheet was pre-formed with 11.5-cm, 45° lifted ends on the front and back, and can be removed for replacement due to wear. A traced outline of the GPR antenna, on the center bottom section of the PVC sheet, was removed to allow direct antenna-to-ground coupling.

The skid attaches to the all-terrain utility vehicle via a ball-receiver hitch, and can be both pulled forward or pushed backward during navigation. The overall weight of the skid is double the weight of the GPR antenna, making the combined weight of antenna and skid to be 57 kg. The skid secures, protects, and stabilizes the GPR antenna during operation, while also compacting and smoothing tilled field surfaces for increased antenna-to-ground coupling.

DGPS Control and Interpolation Software

Proprietary CONTROL and INTERPOLATION software programs were developed in-house using Microsoft Visual Basic 6.0. The CONTROL program executes on a laptop during the survey and performs the following basic tasks: 1) captures one-s data bursts from the GPS transmitter which is connected to the laptop serial port, 2) calculates distance traveled from the previous GPR marker, 3) toggles an external Marker Control relay via the laptop parallel port once a pre-defined distance has been traveled, and 4) records GPS coordinates for each GPR marker in a Marker Database. During post processing of the radar image files, the INTERPOLATION program does a scan number look-up of individual scans within a GSSI RADAN NT Layer File by referencing the Marker Database. A resulting ArcView-compatible database is created which contains target GPS coordinates and depths (fig 3.3).

Research Site

Testing of the mobilized GPR system was conducted in the Cumberland Plateau physiographic region, southeastern U.S.A., near Crossville, TN (fig 3.4). Site elevations ranged from 579 m to 590 m. The site soils were previously mapped as a Hartsells fine sandy loam and a Crossville loam, both underlain by sandstone bedrock found in the upper one m of the soil profile (USDA, 1950). All areas surveyed had grass-blend vegetative covers.

METHODS

Survey accuracy tests were conducted to determine if signal interference existed between system components (i.e., skid, radar antenna, GPS antenna). Thirteen flags, spaced 5-m apart, were placed along a 60-m survey transect. Continuous radar profiles were taken along each side of the flags with the center of the GPR antenna offset 0.8 m from the transect. Three different survey methods were used; 1) Method A, GPR antenna skid with DGPS controlled marker locations, 2) Method B, GPR antenna skid and manually inserted markers (no GPS), and 3) Method C, the traditional method of GPR antenna and manually inserting markers (no GPS or skid). Both Methods B and C required two operators; one to drive and the other to position GPR markers at flag locations. Post-processing of GPR data included distance normalization based on marker locations and high-pass horizontal filtering to remove some horizontal banding.

To evaluate the efficiency of the mobilized GPR system and determine the linear survey-time equations for the mobilized and traditional survey techniques, survey and mapping speeds were recorded using Methods A and C for a fixed number of GPR marker locations. Times for GPR and GPS post-processing and GIS integration were recorded in a lab environment. All times recorded represent a total GPR survey from initial equipment setup to GIS integration and mapping of interpreted subsurface features, excluding site travel times, technical interruptions, etc. Data-acquisition times for Method A and C were recorded for acquiring 10 marker locations along a 45-m transect, and 50 marker locations along a 245-m transect, each on 5-m spacing. Data acquisition times were added to post-processing times, and a total of four times or two times for each survey method were calculated based on 10 and 50 marker locations.

The overall efficiency for GIS database integration using the mobilized GPR system for surveying long transects was evaluated on a 0.8-ha plot. Marker locations, spaced 10 m apart, and GPR scans were recorded continuously while traversing the field in an oblong pattern, starting along the plot perimeter, and spiraling toward the plot center. A continuous transect, with 203 CONTROL software marker locations was recorded.

RESULTS AND DISCUSSION

Survey Accuracy

The resultant post-processed GPR data (fig. 3.5) from tests conducted along the 60-m transect were interpreted by a trained GPR operator, and depths-to-bedrock, based on a two-way travel time in ns, were recorded for each of the 13 flag locations. Depths to bedrock were correlated between the control scan attained with Method C and the tested Methods A and B. With coefficient of correlation values (r) above 0.99 for each of these tests, and interpreted visual similarities, results of these tests indicate that the DGPS system and antenna skid produced little or no interference.

An additional test and subsequent statistical analysis was run on 30-m sections of each 60-m transect acquired using survey Methods A, B, and C. Each of these 30-m transects were distance normalized and numeric values for each pixel were recorded in an ASCII text. Each 30-m transect, after normalization, contained 1051 scans with 512 samples per scan, yielding 768,512 observations. A simple correlation analysis was run to compare Method C with Methods A and B. Highly moderate r-values of 0.65 and 0.63, respectively, further indicate that little interference was incurred as a result of the DGPS equipment and/or GPR antenna skid. Higher correlation values from this analysis are probable with increased confidence in transect positional accuracy and uniformity in GPR system calibrations.

Increased Efficiency[1]

With the use of CONTROL software marker positioning, the mobilized GPR survey system required one operator for data-acquisition, resulting in overall increased efficiency. To illustrate the effectiveness of the mobilized survey system compared to a traditional GPR survey, task times were recorded for Methods A and C, and consolidated to represent overall times for data-acquisition, and post-processing (Table 3.1). Based on total survey times for both survey methods, using points for 10 and 50 marker locations, linear equations were derived to predict the survey time given an infinite number of marker locations spaced five m along a transect (fig. 3.6). Although Method A requires more time for initial setup, indicated by a higher y-intercept, the rate of variable change over time is much less than Method C. The two lines intersect at 15 points, which suggests that any GPR survey transect over 70 m would be more efficient with the use of this mobilized GPR system. When comparing recorded survey times for Methods A and C, at 50 GPR marker locations, the mobilized GPR system reduced data-acquisition and post-processing times by half.

[1] Data and subsequent equations recorded from the study site under described conditions are considered empirical; however, the data and derived equations do reflect general comparison results among the survey methodologies.

GIS Database Integration

With the use of in-house developed software and commercially available RADAN for Windows NT Version 2.092 software, researchers were able to successfully integrate GPR feature data into a GIS software database. While it is possible to manually integrate GPR data into a GIS system database, the CONTROL and INTERPOLATION software developed in this study were proven efficient. Once GPR data were transferred to a desktop PC, 737 interpretations of depth-to-bedrock, from over a 2-km long transect, were made by a trained technician. With the use of INTERPOLATION software, geographical locations of interpretations were generated from a look-up table created by the CONTROL software, and a GIS compatible data-table was created. Once the table was added to a GIS database, a resultant topographical map of the subsurface bedrock (fig. 3.7) was generated using surface interpolation in ArcView. If interpretations were only made at marker locations using survey time equations generated from the efficiency studies, a GIS map could be generated in 513 min using Method C. This can be compared to 119 minutes to interpret the same number of points from the Method A survey. Using Method A surveying techniques, based on 203 marker locations at 5-m spacing, the mobilized GPR method is over 400% more efficient in GIS integration and mapping. With use of the mobilized GPR systems, researchers can accurately map, in a GIS platform, the spatial variability of any number of subsurface features detected by GPR with efficiency.

SUMMARY AND CONCLUSIONS

Geophysical technologies, like GPR, are beneficial to a variety of subsurface investigations. The ability to rapidly acquire and disseminate GPR data is crucial for increasing efficiency and subsurface mapping precision. A mobilized platform was developed to efficiently map subsurface features using GPR. Key components of this mobilized system include an in-house designed antenna skid, and DGPS control and interpolation software used for GPR marker positioning and rapid integration of feature data into a GIS database.

This project demonstrates that the use of DGPS marker positioning and the antenna skid increased survey efficiency with little loss in survey accuracy when compared to a traditional GPR survey. A traditional GPR survey technique was compared to a mobile survey system with DGPS marker positioning. Data were interpreted manually, and depths to subsurface bedrock were compared. Coefficient of correlation values, derived from visually interpreted data, greater than 0.99, and visual similarities indicate no interference from system components. Further statistical analysis, comparing images on a pixel-by-pixel basis, resulted in moderately high correlations between a control scan and two other scans utilizing mobilized GPR system equipment (GPR antenna skid and DGPS antenna). Use of this system required only one person as driver and GPR operator, thereby reducing the need for additional labor costs and trained operators. Use of DGPS control software also increased efficiency by eliminating the need for pre-surveyed marker locations. When comparing recorded survey times for the mobilized GPR system and a traditional GPR survey for 50 marker locations, the mobilized GPR system reduced data-acquisition and post-processing times by half.

With the use of in-house developed CONTROL and INTERPOLATION software and commercially available GSSI RADAN NT software, researchers were able to integrate efficiently and precisely GPR feature data, depth-to-bedrock in the study, into a GIS database. Although integrating GPR feature data into a GIS database using traditional surveying techniques is possible, this study shows that integration of GPR feature data into a GIS database is over four times more efficient. Overall, larger tracts of land can now be surveyed with GPR, merged with DGPS locational data, and integrated into a GIS database.

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PART III APPENDIX

Table 3.1. Survey times for 10 and 50 GPR markers using Methods A and C

Method	Markers*	Data acquisition time (min)	Post-processing time (min)	Total survey time (min)
A	10	54	20	75
C	10	40	24	63
A	50	60	24	84
C	50	110	47	157

*** Based on a marker spacing of 5 m**

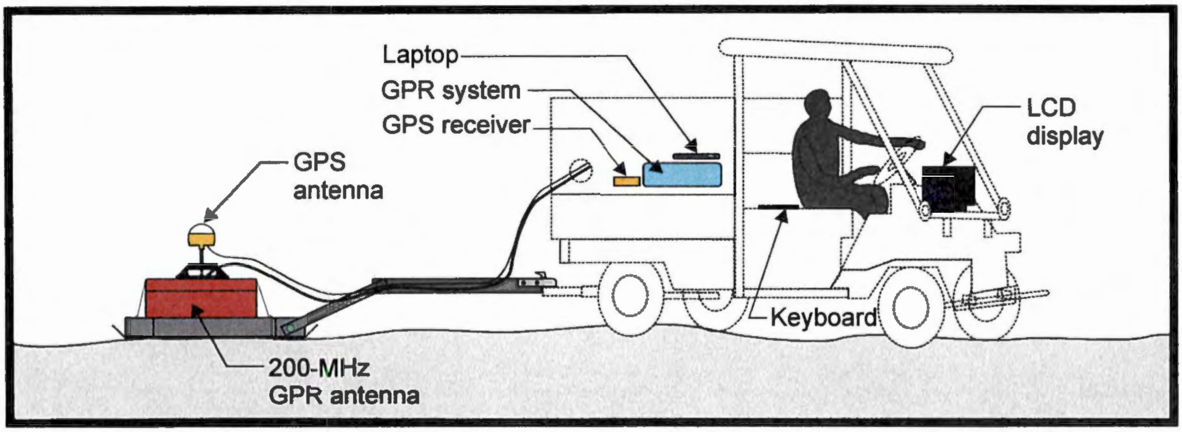


Figure 3.1. Components of the mobilized GPR system for rapid subsurface imaging

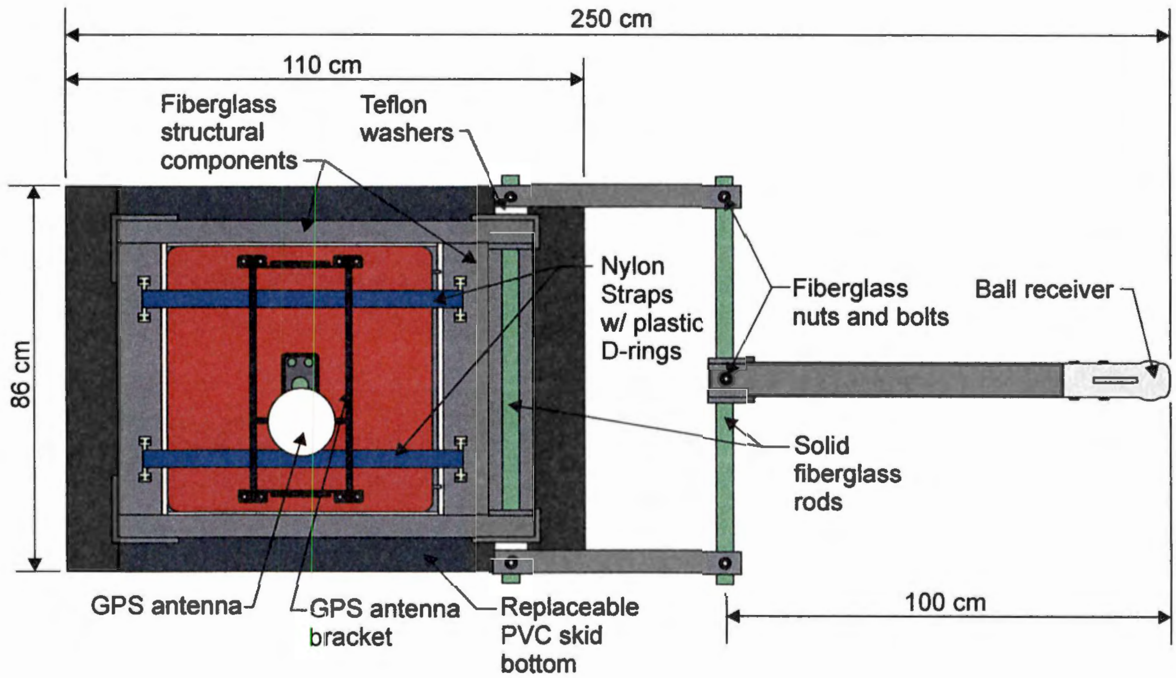


Figure 3.2. GPR antenna skid shown with 200-Mhz GPR antenna and real-time DGPS positioning

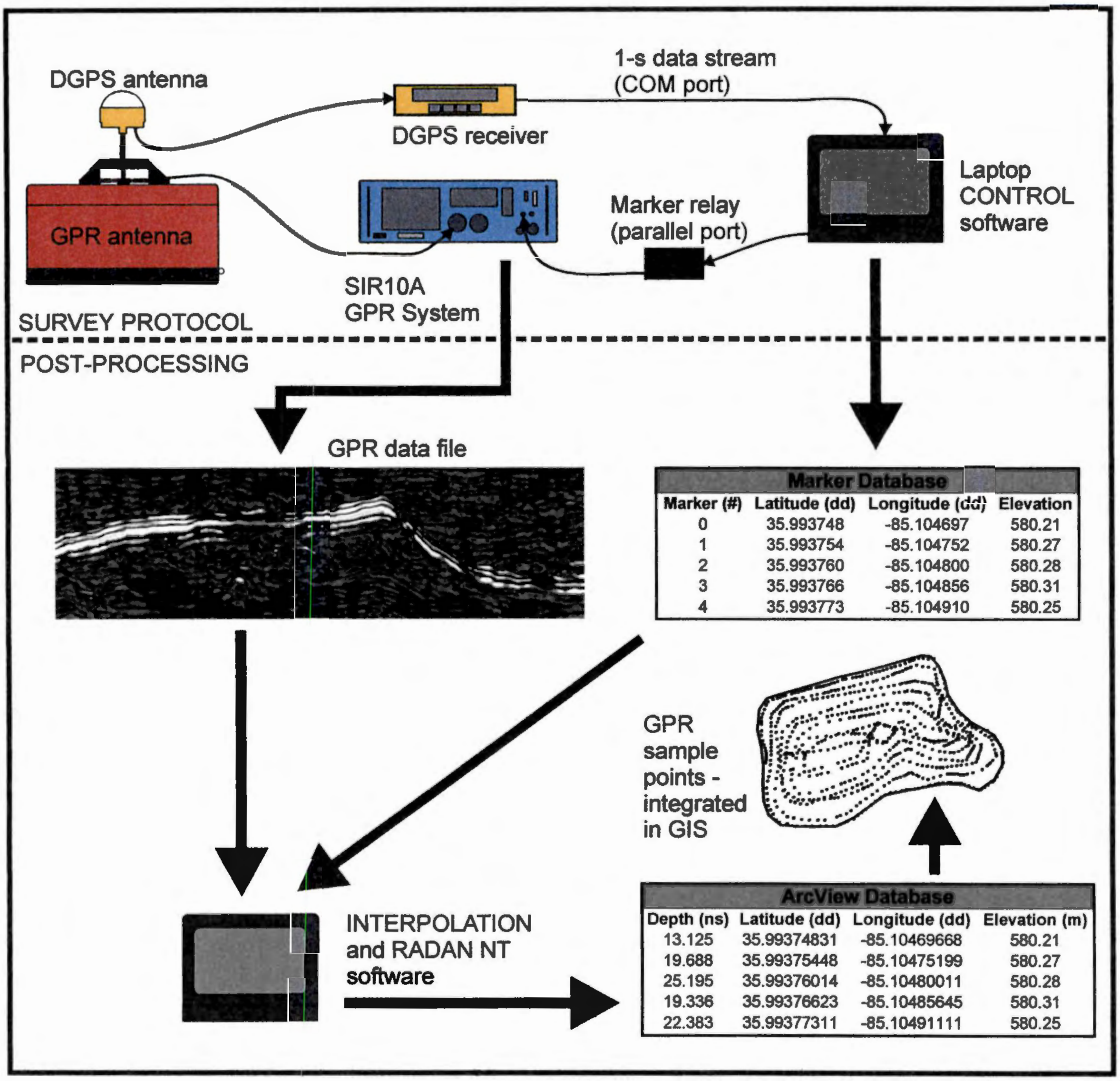


Figure 3.3. ArcView database creation using DGPS CONTROL and INTERPOLATION software

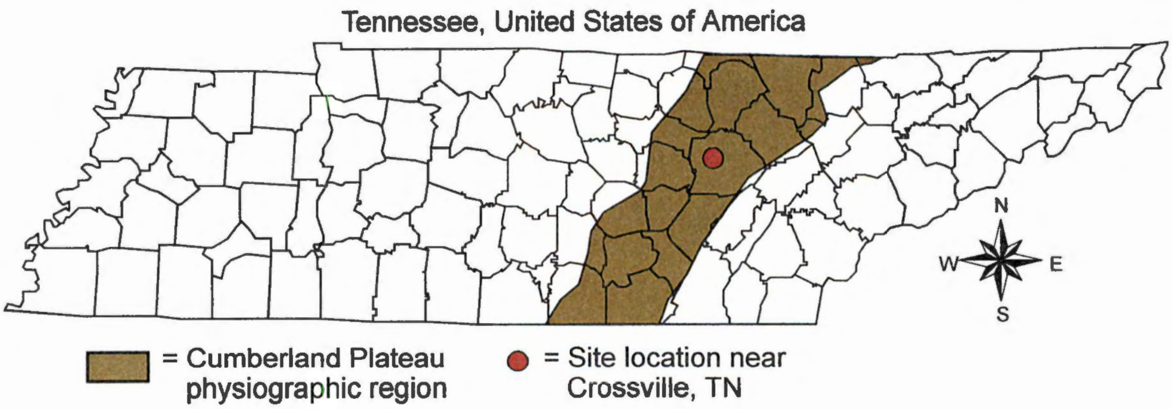
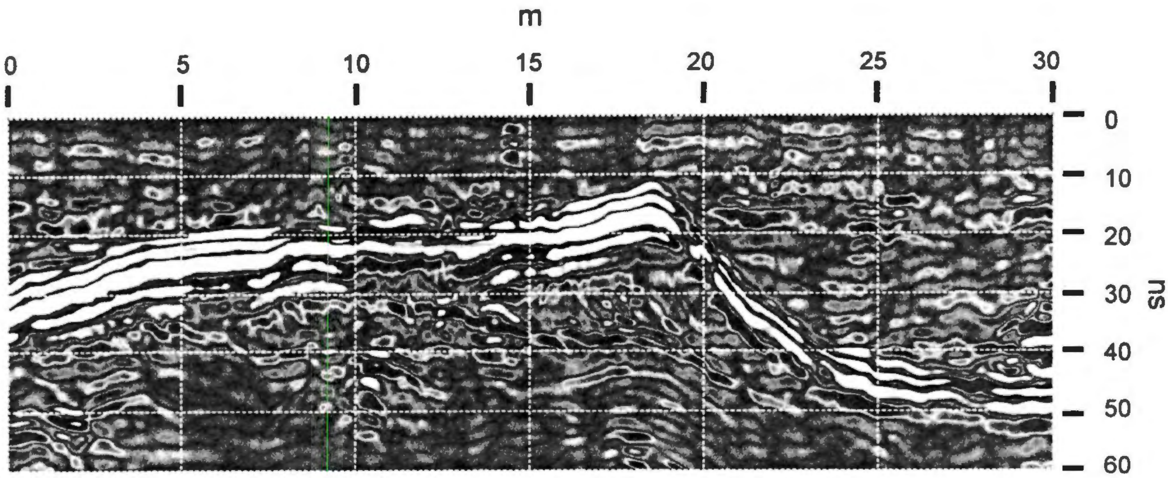
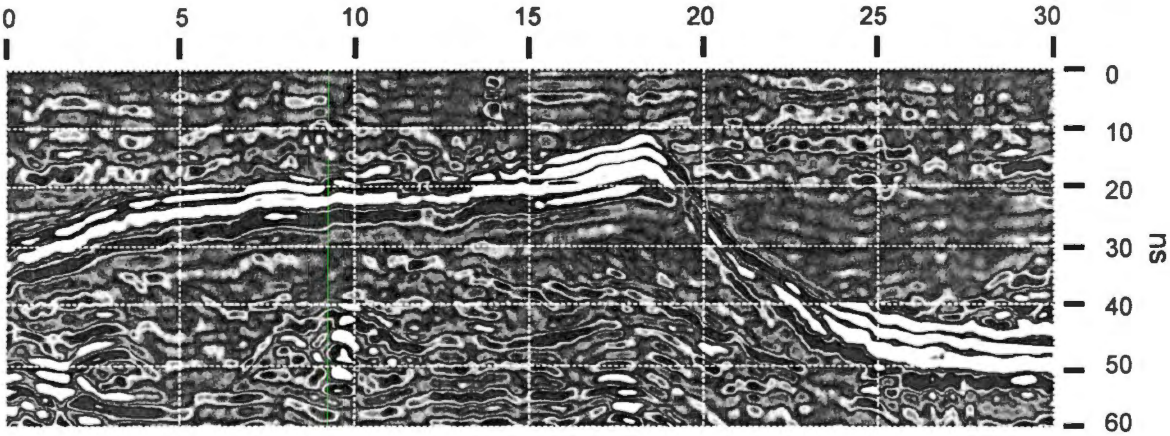


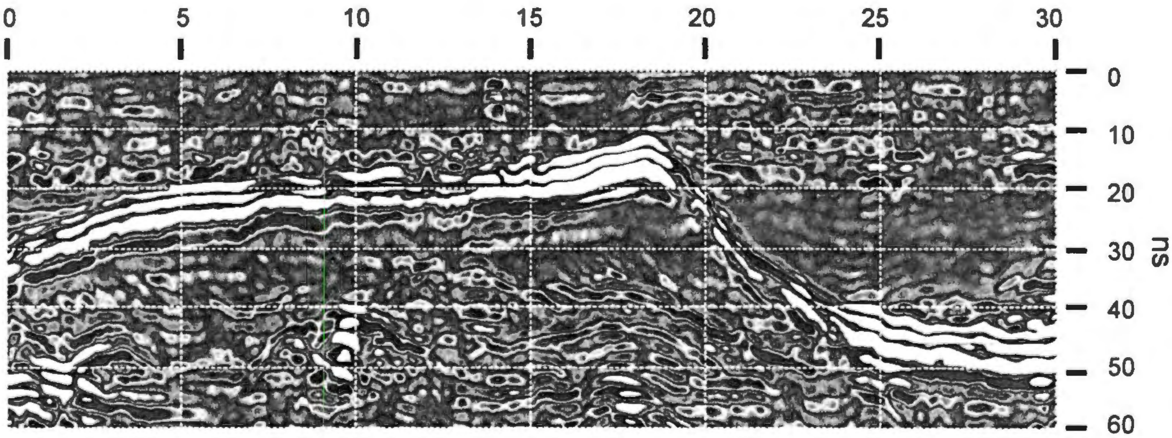
Figure 3.4. Site location for mobilized GPR system testing



Method A - GPR antenna and skid with DGPS controlled marker positioning



Method B - GPR antenna and skid with manual marker positioning



Method C - GPR antenna alone with manual marker positioning

Figure 3.5. GPR scans using Methods A, B, and C - note visual similarities and equal depths to subsurface bedrock interface

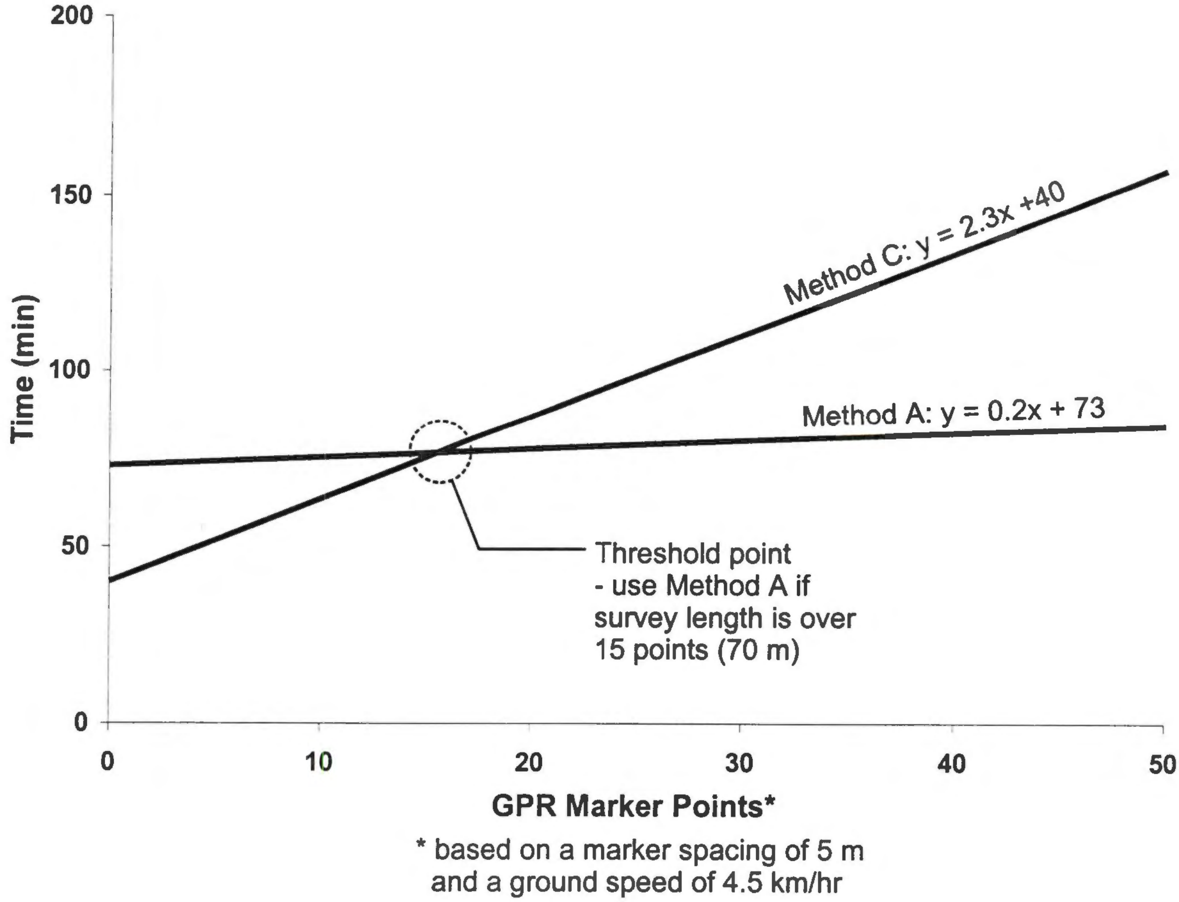


Figure 3.6. Linear models for predicting survey times using Method A (DGPS CONTROL software), and Method C (manually controlled marker locations)

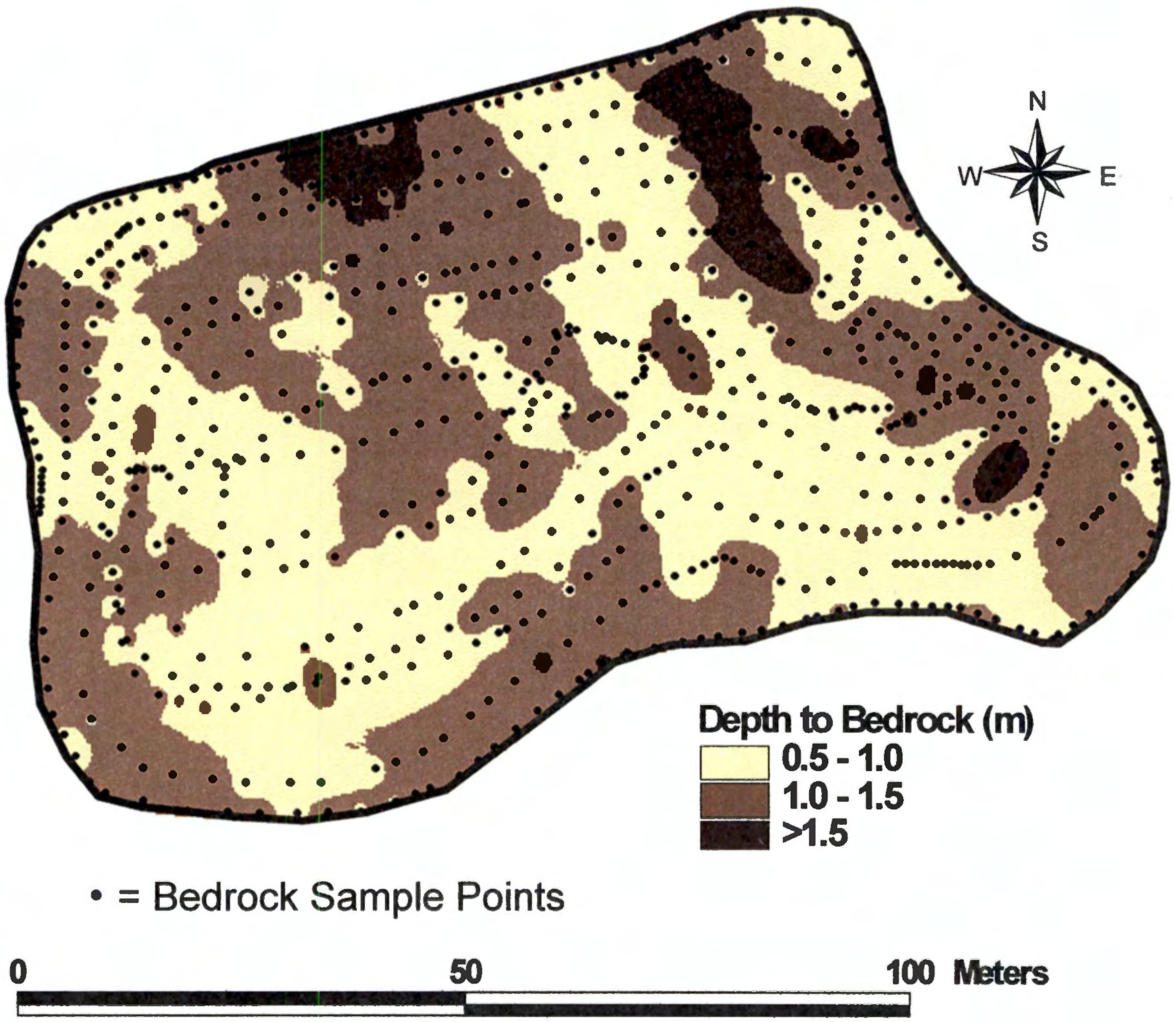


Figure 3.7. Subsurface topography map of sandstone bedrock interpolated in ArcView GIS from737 sample points generated by the interactive interpretation feature in GSSI RADAN NT and INTERPOLATION software

PART IV

SUMMARY

Mobilizing non-intrusive geophysical instrumentation and linking recorded samples with geographical positional data increases subsurface mapping efficiency. This study reports on two mobilized, field survey systems: a mobile EMI survey system and a mobile GPR survey system, both linked with DGPS positioning. Both mobile systems have practical applications for a variety of subsurface explorations.

The mobile EMI survey system was originally designed as a reconnaissance tool for tracking subsurface water and/or agrochemical movement in agricultural production fields. This system is suitable for tracking differences in soil water content because increased water saturation in soils can be correlated to higher conductivity values acquired with EMI instrumentation. The system can also be implemented for a variety of other subsurface investigations when ground conductance or resistance can be correlated to natural features or anthropogenic disturbances. For example, the EMI instrumentation has the ability to detect metal objects; therefore, the mobile EMI survey system would be suitable for locating buried drums, piping, or natural metal formations in the subsurface. Since electrical and magnetic fields also affect the EMI instrumentation, the EMI system could be used to locate power, telephone, and other underground cable lines. Increased salt concentrations in soil also influence conductivity data, so the mobile EMI system could be used to map soil salinity boundaries for agricultural management purposes. Along the same lines, the mobile EMI system can be used to rapidly delineate major soil boundaries in certain areas. The mobile EMI survey system is applicable to a variety of subsurface investigations; however, conditions exist in which the system is not well suited.

In certain situations, the mobile EMI survey system can be limited by overall maneuverability, loss or interference of GPS positioning signals, and/or interference of the EMI instrumentation. The mobile EMI system is not well suited for surveying under any canopy for several reasons. First, due to the combined length of the all-terrain utility vehicle and the instrument cart, the operation of the system is limited to open areas where wide turns can be made. Second, the mobile EMI survey system relies on GPS to accurately position the conductivity samples recorded. The GPS equipment requires signals from satellites that cannot be transmitted through trees, geologic formations, or anthropogenic objects like buildings. Positional errors can also occur when GPS signals are delayed because of signal reflection. For this reason, the mobile EMI survey system works best when positioned away from tall tree lines, buildings, or any other object that blocks or reflects GPS satellite signals. Third, interference from objects above the surface can significantly affect the conductivity data. Anything from vegetation to cars and humans can distort conductivity values. Because interference can be a factor in data quality, the mobile EMI survey system works best in areas where surface ground cover is uniform and there exists no tall or massive sections of vegetation. An ideal survey area would be free from metal objects, unless that is the intended target, and overhead and underground electrical lines and other service cables.

The mobile GPR survey system was developed out of a need to cover larger areas of land when looking for discontinuities or delineations in soil or bedrock profiles. In this particular study, the system was proven particularly useful when tracking changes in bedrock depth over a larger area. The ability to produce continuous images of the subsurface profile coupled with the ability to locate sample locations with integrated GPS makes the mobile GPR survey system a valuable utility for a variety of soil and water research. For example, the mobile GPR system can collect depth-to-bedrock data over an agricultural production field in an area prone to shallow topsoil. This data can be analyzed and exact sample depth locations can be entered into a GIS database. This data can further be interpolated in GIS and subsequent crop management decisions can be made based on available topsoil depth. Ground-penetrating radar is also effective in tracking water table depths in certain soils. The mobile GPR system would allow greater coverage over a much larger area with increased sampling. Since GPR has the ability to detect changes in dielectric properties, the technology is also useful when looking for anthropogenic disturbances. Examples where the mobile GPR survey system could be used to look for disturbances include locating underground utilities, searching for buried drums, looking for buried bodies, or buried ordnance detection. While the mobile GPR survey system has many capabilities, the system also has several limitations that must be considered.

Like the mobile EMI survey system, the mobile GPR survey system is limited to open areas free from interference. The GPR survey system is more maneuverable than the EMI system, but geographical positioning is still limited under a canopy by GPS signal loss or interference. Error in the GPR imaging profile is introduced when the GPR antenna is pulled over rugged terrain. For this reason, the mobile GPR survey system works best on smooth terrain like a lawn or mowed field and does not work well in wooded, rocky, or thickly vegetated areas. Like EMI instrumentation, GPR equipment can also be effected by electrical or magnetic fields. In certain GPR systems, the top of the antenna is not shielded, and imaging can be distorted by metal in close proximity to the radar antenna or objects above the antenna. Limitations in the system exist due to operating limitations of the GPR system used. Depending on the GPR unit used, most manufacturers have recommended temperature ranges in which the unit can be operated. In addition, certain soils and certain soil conditions limit the effectiveness of the GPR signal to penetrate a particular medium. In general, GPR signal penetration is most effective in soils with low clay content and high sand content. Increased water content in soils is the limiting factor in many situations. For this reason, GPR imaging is most effective when the soil is well drained.

Realizing that both EMI and GPR data can be distorted by interference from a variety of sources, the objectives of this study included development of two mobile systems that did not interfere with data quality. Once these systems were developed in a way that did not interfere with the equipment being used, the second objective included testing the overall effectiveness and efficiency of the two systems. To meet these objectives, extensive testing was conducted on both systems, which included interference testing between system components, efficiency studies, and overall effectiveness of both systems for mapping subsurface features.

Interference testing was conducted on both mobile survey systems. Conductivity samples, taken at two different depths, were recorded using a manual EMI survey. These values were compared to other conductivity values taken at the same locations with the mobile EMI survey system. Coefficient correlation values of 0.90 and 0.96, for two depths, indicate little interference from the mobile EMI survey system components. Similar interference testing was conducted on the mobile GPR survey system. A transect with reference locations was surveyed using a manual GPR survey technique, then again with the mobile survey technique. Depth-to-bedrock was interpreted for both sets of data and compared. Coefficient of correlation values greater than 0.99 indicate little interference from the mobile GPR survey system components. Further testing was conducted to compare pixel values for the two different GPR scans. Moderately high coefficient of correlation values further indicate little interference from the mobile GPR survey system components.

Efficiency studies were conducted on both mobile survey systems. For both systems, times involved during traditional and mobile surveys were recorded and compared for data-acquisition and post-processing efficiency. Results show that the EMI mobile survey system increased sampling rates by a factor >100 when compared to a traditional EMI survey. Results from the comparison between a traditional GPR survey and the mobile GPR system illustrate that the mobile system reduced data-acquisition and post-processing times by half.

Times from the efficiency studies of both mobile survey systems were used to develop linear models that can be used to predict future survey times. These models were then plotted with linear models developed from traditional survey time data. Results of these models indicate that when surveying more than 23 points with EMI, the mobile EMI survey system should be implemented instead of the traditional survey technique.

Likewise, when surveying a GPR transect over 70 m in length, the mobile GPR survey system is preferred over a more conventional GPR survey.

Data from this project shows that precision mapping of subsurface features are possible with increased survey efficiency and incorporation of DGPS positioning. Results show that the mobile EMI survey can increase mapping resolution by a factor of >10; however, the same resolution can be obtained with the conventional manual EMI survey given enough time. In fact, based on a 1-ha study site with 1947 recorded conductivity samples, 0.5 workdays were required to produce a geographically referenced and surface interpolated conductivity map using the mobile EMI survey system. This time can be compared to 8.5 workdays theoretically necessary to produce the same map using the conventional manual EMI survey.

Increased mapping efficiency and precision are also possible with the mobile GPR survey system. Using CONTROL software, GPR marker locations are referenced with DGPS coordinates. RADAN NT and INTERPOLATION software further increase mapping precision. RADAN NT allows an operator to interpret depth-to-target between marker locations and assign that interpretation to a GPR scan number. INTERPOLATION software automatically assigns geographical coordinates to any interpreted scan. This data can then be efficiently integrated in a GIS database for interpolation and mapping. Results of this study, based on a 0.75 ha site with 203 GPR marker locations spaced five m apart, show that mapping with the mobilized GPR survey system is 400% more efficient than a traditional GPR survey.

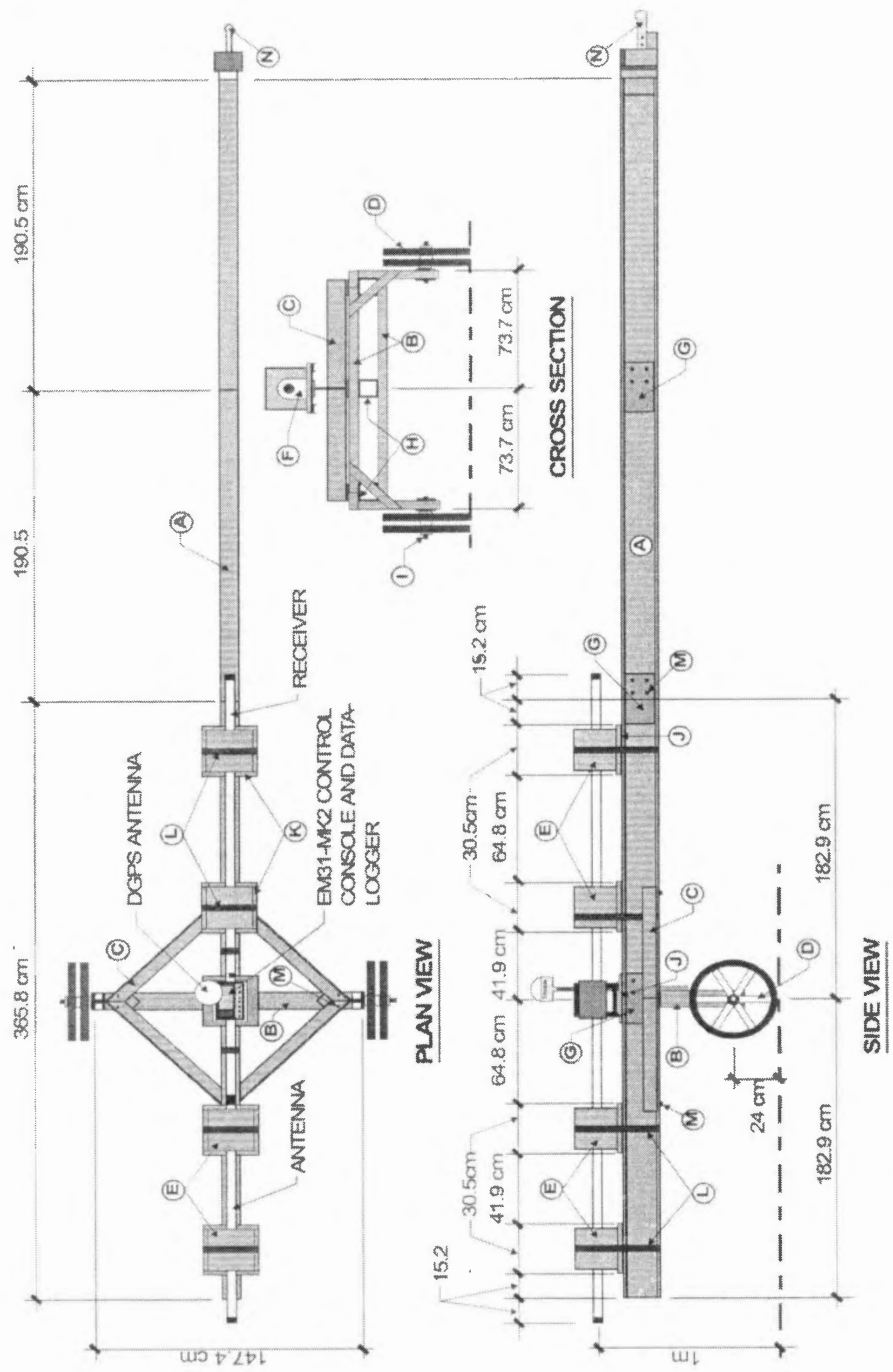
Results of this study demonstrate that both mobile survey systems were proven effective for rapid subsurface data-acquisition. Both systems are designed to survey larger areas than commonly surveyed in the past. For this reason, both survey systems are well suited for reconnaissance prior to more intrusive and expensive sampling. The mobile EMI and GPR survey systems can be used in conjunction with one another depending on the particular site. For example, due to data storage restrictions, the mobile EMI survey system can be used to delineate natural feature breaks on a given landscape. These breaks can be mapped and located for a more intensive survey with the GPR survey system. The systems can also be used separately, but in conjunction with different intrusive or non-intrusive sampling techniques. For example, both the EMI and GPR mobile survey systems could be used to locate buried metal drums; however, depending on the site and individual abilities of both systems, one system might prove to be a better choice when looking for the drums.

With the ability to efficiently and accurately acquire, locate, and process data about the subsurface, expense is decreased and accuracy is increased when making management decisions. This study demonstrates that subsurface data acquisition and mapping efficiency is greatly enhanced with the utilization of non-intrusive geophysical equipment. By increasing the mobility of geophysical equipment as well as the positional accuracy and efficiency of recorded samples, the use of mobile survey systems for non-intrusive geophysical instrumentation will become more prevalent in a variety of subsurface investigations.

APPENDIX

EMI Instrument Trailer

See component tables for materials and sizes



EMI Instrument Trailer Component Tables

Materials list for EMI trailer with component names and materials

Label	Component	Material
A	I-beam	EXTREN® Series 500 fiberglass*
B	Rectangular tube	EXTREN® Series 500 fiberglass*
C	Equal leg angle	EXTREN® Series 500 fiberglass*
D	Wheels	Polymer Plastic and hard rubber
E	PVC welded boxes	PVC with welded joints
F	Instrument supports	Medium density foam
G	Plates	EXTREN® Series 500 fiberglass*
H	Square tube	EXTREN® Series 500 fiberglass*
I	Round rod	Thermal cure rod – solid resin fill*
J	Plates	EXTREN® Series 500 fiberglass*
K	Square tube	EXTREN® Series 500 fiberglass*
L	Straps and buckles	Nylon strapping and plastic buckles
M	Nuts and bolts	FIBERBOLT® fiberglass*
N	2" ball receiver	Steel

* These products are manufactured by the Strongwell Corp. in Bristol, VA

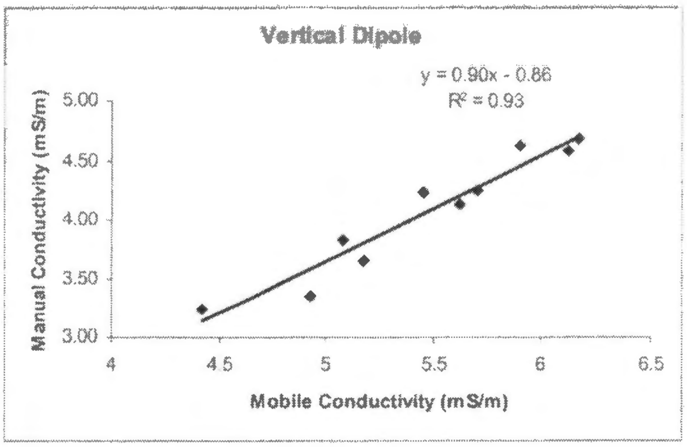
Size and description of EMI trailer components

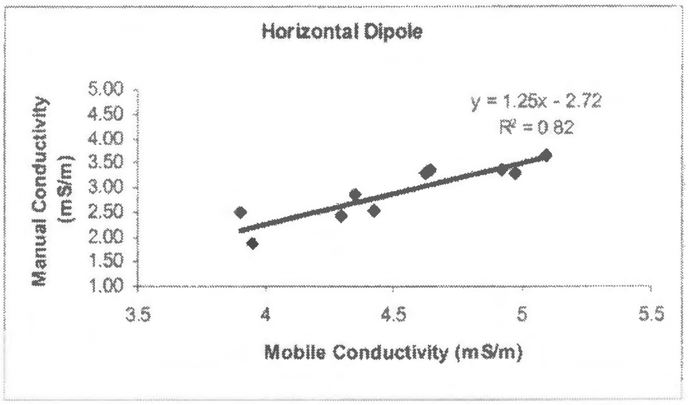
Label	Stock Size	Description
A	8 x 4 x 3/8"	Trailer body structural component
B	4 x 1/8 x 2 x 1/4"	Chassis structural component
C	3 x 1/4"	Braces
D	19"	(4) hard rubber wheels
E	1/4"	Encasement for foam supports
F	10 x 10" blocks	Hollowed and cut to fit
G	1/2"	Epoxied on one end to I-beam
H	4 x 1/4	Epoxied spacers for rect. tube
I	1 1/2"	Axles
J	1/8"	PVC box platform
K	1 x 1/8"	Rails for PVC box platform
L	1 1/2"	Used to secure boxes to platform
M	1/2" – 13 UNC	Used to assemble trailer
N	1 7/8" ball – 9" long	Connection to ball hitch on ATV

Raw Data and Tables from EMI Data Quality Tests

Recorded at Ames Plantation – 11/29/00

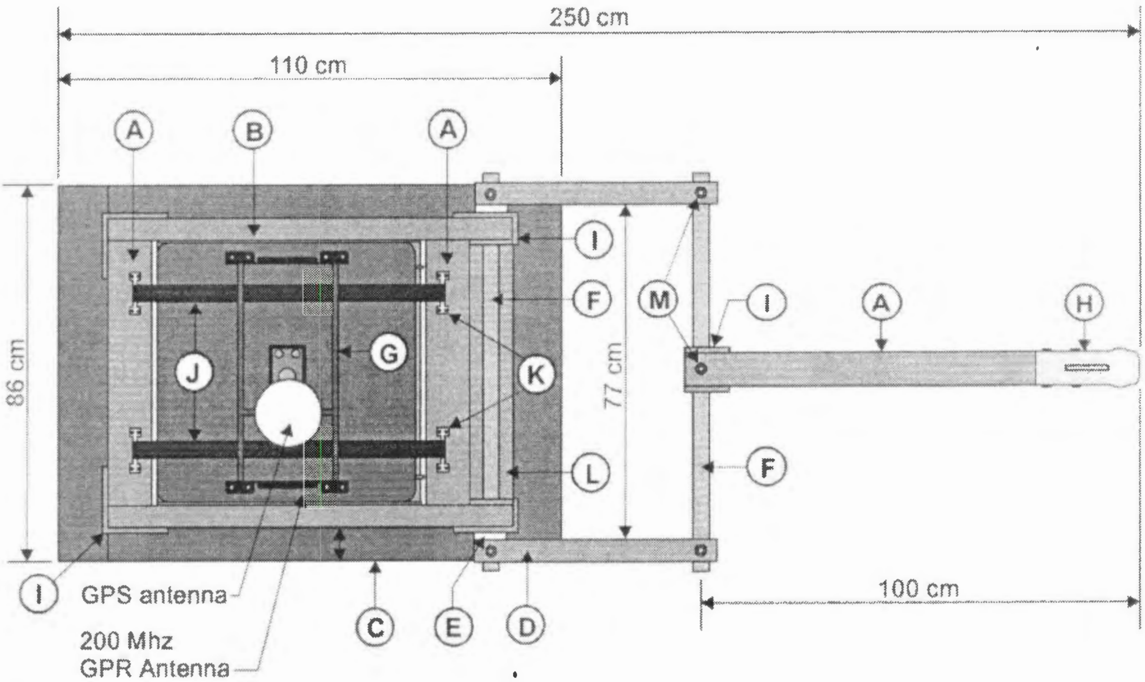
Vertical Dipole		
Test #	Mobile Test	Manual Test
1	5.45	4.225
2	5.075	3.825
3	4.425	3.225
4	4.925	3.35
5	5.175	3.65
6	5.7	4.25
7	6.175	4.675
8	5.9	4.625
9	5.625	4.125
10	6.125	4.575
Horizontal Dipole		
1	4.3	2.425
2	4.35	2.85
3	3.9	2.475
4	3.95	1.875
5	4.425	2.525
6	4.975	3.3
7	5.1	3.65
8	4.625	3.3
9	4.65	3.35
10	4.925	3.375



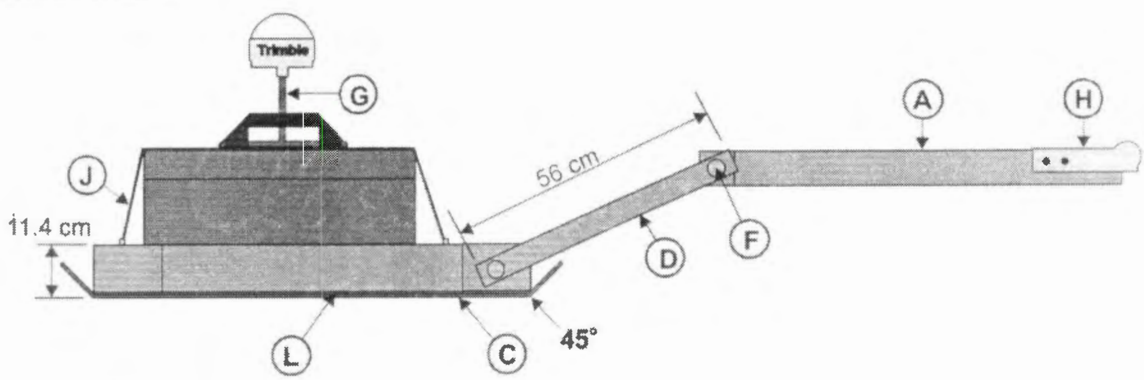


GPR Antenna Skid

See component tables for materials and sizes



PLAN VIEW



SIDE VIEW

GPR Antenna Skid Component Tables

Materials list for EMI trailer with component names and materials

Label	Component	Material
A	Square tube	EXTREN® Series 500 fiberglass*
B	Rectangular tube	EXTREN® Series 500 fiberglass*
C	Plastic sheet	PVC
D	Square tube	EXTREN® Series 500 fiberglass*
E	Plastic washer	Teflon
F	Round rod	Thermal cure rod – solid resin fill*
G	Plastic Pipe	PVC
H	1 7/8" ball receiver	Galvanized steel
I	Plate	EXTREN® Series 500 fiberglass*
J	Straps and buckles	Nylon strapping and plastic buckles
K	Strap loops	Galvanized steel
L	Plate	EXTREN® Series 500 fiberglass*
M	Nuts and bolts	FIBERBOLT® fiberglass*

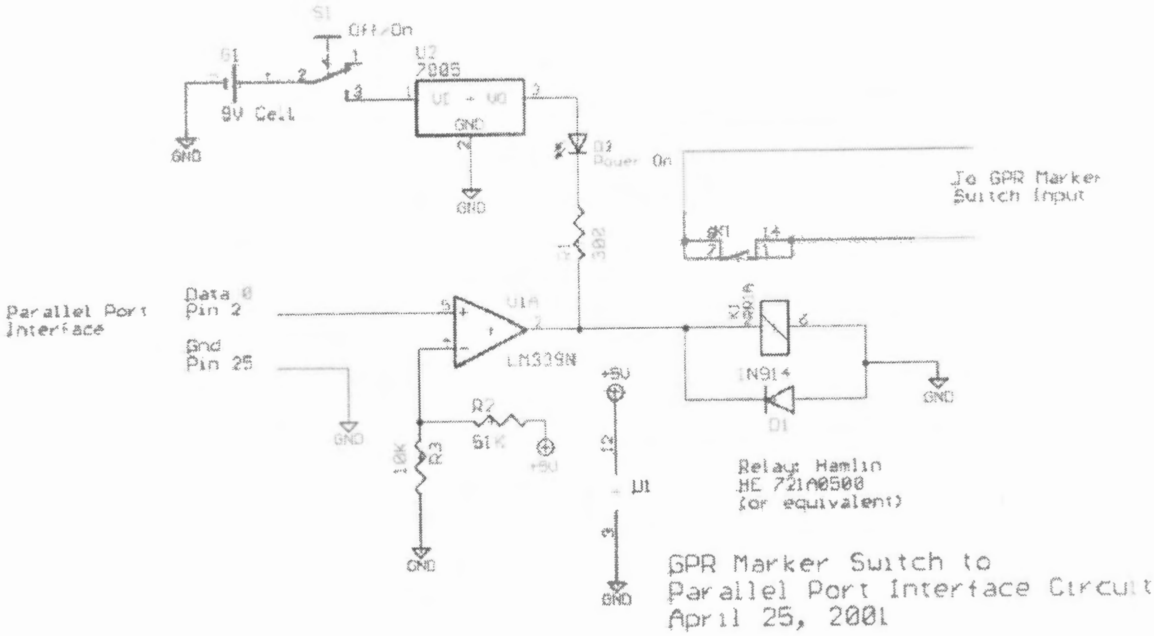
* These products are manufactured by the Strongwell Corp. in Bristol, VA

Size and description of EMI trailer components

Label	Stock Size	Description
A	4" x 4"	Used in antenna frame and skid tongue
B	2" x 4"	Used in antenna frame
C	¼"	Replaceable plastic bottom
D	2" x 2"	Used in hinge mechanism
E	1 ½" i.d. and 3" o.d.	Hinge friction reducer
F	1 ½"	Used in hinge mechanism
G	½"	GPS antenna bracket
H	1 7/8" ball – 9" long	Connection to ball hitch on ATV
I	½"	Used for support and rigidity
J	1 ½"	Firmly secures GPR antenna to skid
K	3" x 1" x ¾"	Tie-downs for nylon straps
L	¼"	Used to support antenna frame
M	½" – 13 UNC	Used to assemble hitch mechanism

GPR Marker Control Relay

Designed by David Smith



Documented GPR Survey Task Times

Method A – 10 GPR Marker Locations

Data Acquisition	
Task	Time
Setup antenna skid	619
Setup SIR-10 GPR system (200Mhz antenna)	742
Setup DGPS antenna, receiver, power supply, and laptop (DGPS components)	265
Setup marker relay, KVM components	287
Radar calibration (excluding tape format)	192
Data acquisition time (recorded from GPS time stream)	67
Breakdown marker relay, and KVM components	173
Breakdown DGPS antenna receiver, power supply, and laptop (DGPS components)	186
Breakdown SIR-10 GPR system (200Mhz antenna)	502
Breakdown antenna skid	235
TOTAL	**3268**
Data-download	
Task	Time
Setup GPR data-download equipment	289
GPR data download	196
Breakdown GPR data-download equipment	234
Transfer of GPS files from laptop to desktop	105
TOTAL	**824**
Post-processing	
Task	Time
Interpretation of selected interface depths (Layer File creation)	125
Creation of GIS database file from INTERPOLATION software	15
Creation of ArcView project file and integration of database file	193
Surface interpolation of sample points	72
TOTAL	**405**

Documented GPR Survey Task Times

Method A – 50 GPR Marker Locations

Data Acquisition	
Task	**Time**
Setup antenna skid	619
Setup SIR-10 GPR system (200Mhz antenna)	742
Setup DGPS antenna, receiver, power supply, and laptop (DGPS components)	265
Setup marker relay, KVM components	287
Radar calibration (excluding tape format)	443
Data acquisition time (recorded from GPS time stream)	167
Breakdown marker relay, and KVM components	173
Breakdown DGPS antenna receiver, power supply, and laptop (DGPS components)	186
Breakdown SIR-10 GPR system (200Mhz antenna)	502
Breakdown antenna skid	235
TOTALS	**3619**
Data-download	
Task	**Time**
Setup GPR data-download equipment	289
GPR data download	296
Breakdown GPR data-download equipment	234
Transfer of GPS files from laptop to desktop	105
TOTALS	**924**
Post-processing	
Task	**Time**
Interpretation of selected interface depths (Layer File creation)	216
Creation of GIS database file from INTERPOLATION software	15
Creation of ArcView project file and integration of database file	193
Surface interpolation of sample points	72
TOTALS	**496**

Documented GPR Survey Task Times

Method C – 10 GPR Marker Locations

Note: x2 indicates two operators required

Data Acquisition			
Task	**Time (s)**		
Flag placement @5m with 50m survey tape - linear transect	151	x2	302
Setup DGPS antenna, receiver, and power supply	276	x2	552
Survey GPR marker points with DGPS - 1 point/flag	134	x2	268
Breakdown DGPS antenna, receiver, and power supply	129	x2	258
Setup SIR-10 GPR system (200Mhz antenna)	371	x2	742
Radar calibration (excluding tape format)	192	x2	384
Data acquisition time	100	x2	200
Flag removal	19	x2	38
Breakdown SIR-10 GPR system (200Mhz antenna)	251	x2	502
		TOTAL	2392

Data-download			
Task	**Time**		
Setup GPR data-download equipment	289		289
GPR data download	196		196
Breakdown GPR data-download equipment	234		234
Transfer of GPS files from palmtop to desktop	95		95
		TOTAL	814

Post-processing			
Task	**Time**		
Interpretation of selected interface depths (manual record)	283		283
Spreadsheet compilation of marker locations with marker depths	50		50
Creation of ArcView project file and integration of database file	193		193
Surface interpolation of sample points	72		72
		TOTAL	598

Documented GPR Survey Task Times

Method C – 50 GPR Marker Locations
Note: x2 indicates two operators required

Task	Time		
Data Acquisition			
Flag placement @5m with 50m survey tape - linear transect	944	x2	1888
Setup DGPS antenna, receiver, and power supply	276	x2	552
Survey GPR marker points with DGPS - 1 point/flag	497	x2	994
Breakdown DGPS antenna, receiver, and power supply	129	x2	258
Setup SIR-10 GPR system (200Mhz antenna)	371	x2	742
Radar calibration (excluding tape format)	443	x2	886
Data acquisition time	261	x2	522
Flag removal	132	x2	264
Breakdown SIR-10 GPR system (200Mhz antenna)	251	x2	502
		TOTAL	6608
Data-download			
Setup GPR data-download equipment	289		289
GPR data download	296		296
Breakdown GPR data-download equipment	234		234
Transfer of GPS files from palmtop to desktop	100		100
		TOTAL	919
Post-processing			
Interpretation of selected interface depths (manual record)	1352		1352
Spreadsheet compilation of marker locations with marker depths	254		254
Creation of ArcView project file and integration of database file	193		193
Surface interpolation of sample points	72		72
		TOTAL	1871

GPR Survey Accuracy Test Data

Interpreted Depth to Bedrock

Distance (m)	Method C (ns)	Method B (ns)	Method A 9ns)
0	11.0	13.4	12.4
5	19.4	19.4	19.7
10	23.6	23.8	24.1
15	19.1	20.0	19.3
20	21.6	22.9	21.4
25	30.3	29.3	29.8
30	21.0	21.2	21.3
35	19.1	19.1	18.6
40	16.8	17.6	17.6
45	20.7	22.0	20.0
50	41.6	43.2	42.8
55	45.0	46.6	45.6
60	57.9	58.4	56.0

SAS Program for GPR Survey Accuracy Tests

```
filename ta1 'ta1.csv';
data t1; infile ta1 dlm='09'x lrecl=10000 pad;
    input t1 @@;
    if t1 ne .;
filename tb1 'tb1.csv';
data t2; infile tb1 dlm='09'x lrecl=10000 pad;
    input t2 @@;
    if t2 ne .;
filename ta2 'ta2.csv';
data t3; infile ta2 dlm='09'x lrecl=10000 pad;
    input t3 @@;
    if t3 ne .;

data pixels; merge t1 t2 t3;
    retain n 0;
    t1t2 = t1 - t2;
    t1t3 = t1 - t3;
    t2t3 = t2 - t3;
    row = floor(n/1501) + 1;
    column = mod(n,1501) + 1;
    n + 1; drop n;
    row = 504 - 8*floor((row-1)/8) + 1;
    column = 20*floor((column-1)/20) + 1;

options ls=72;
proc corr; var t1 t2 t3;

proc summary nway data=pixels; class row column;
    var t1t2 t1t3 t2t3;
    output out=grid mean= max=maxt1t2 maxt1t3 maxt2t3;
run;
```

Name and Descriptions of Files Used in Thesis
-Recorded on compact disc-

FILE NAME	FILE DESCRIPTION
FORWARD	
graduate_council.doc	Graduate council acceptance letter
introduction.doc	Thesis title page, dedication, acknowledgements, abstract, table of contents, list of table and figures, and list of abbreviations
PART I - GENERAL INTRODUCTION	
partI.doc	Part I document
PART II - MOBILIZED SURVEYING OF SOIL CONDUCTIVITY USING ELECTROMAGNETIC INDUCTION	
partII.doc	Part II document
partII_appendix.doc	Part II appendix document
figures2.1and2.2.cdr	Figures 2.1 and 2.2
figures2.3and2.4.cdr	Figures 2.3 and 2.4
figures2.5and2.6.cdr	Figures 2.5 and 2.6
figures2.7and2.8.cdr	Figures 2.7 and 2.8
emidataqualitytests.xls	Recorded conductivity values for mobile versus manual (Table 2.3)
eminterferencetests.xls	Recorded conductivity values for interference testing between EM instrument and Kawasaki MULE (Figure 2.4)
em_surveytime.xls	Values and graphs used to generate survey time equations for different EM survey techniques (Figures 2.5 and 2.6)
052599_75_150points.dbf	GIS table used to generate points and subsequent IDW interpolations of conductivity values at Ames' Field 75 (Figure 2.7)
031400_75_1947points.dbf	GIS table used to generate points and subsequent IDW interpolations of conductivity values at Ames' Field 75 (Figure 2.8)
EMtrailerasbuiltmetric.cdr	Original design file for the EM trailer
PART III - MOBILE FIELD SYSTEMS FOR RAPID SUBSURFACE SURVEYING USING GROUND-PENETRATING RADAR	
partIII.doc	Part III document
partIII_appendix.doc	Part III appendix document
figures3.1and3.2.cdr	Figures 3.1 and 3.2
figure3.3.cdr	Figure 3.3
figure3.4.cdr	Figure 3.4
figure3.5.cdr	Figure 3.5
figure3.6.cdr	Figure 3.6
figure3.7.cdr	Figure 3.7
GPR_surveyaccuracy_SASstatistics.zip	SAS statistics for GPR survey accuracy tests - also includes normalized and truncated .dat files for Figure 3.5
gprdocumentedsurveytimes.xls	Documented survey times for Method A and Method C (used to develop Table 3.1 and Figure 3.6)
gprdepthtobedrock.xls	Manual interpretation of depth to bedrock from Method A and C GPR data
0426bedrockdepths.dbf	GIS table used to generate points and subsequent IDW interpolations of subsurface bedrock at PES (Figure 3.7)
gpr_transects_figure3.5.zip	Raw .dat files recorded on 03-29-01 (Figure 3.5 - T=GPR, S=GPR+SKID, P=GPR+SKID+GPS)
asbuiltsled.cdr	Original design file for the GPR skid
PART IV - SUMMARY	
partIV.doc	Part IV document
general_appendix.doc	Part IV appendix document
VITA	
vita.doc	Vita document

VITA

Lester Leroy Leonard was born on April 11, 1972 in Kingsport, Tennessee. He attended Dobyns-Bennett High School, and graduated in May 1990. In August of 1991 he entered The University of Tennessee at Knoxville and earned a Bachelor of Science Degree in Agriculture with a concentration in the Environment and Natural Resources in December of 1998. He began his work towards a Masters of Science degree in Biosystems Engineering Technology in January 1999, and was employed as a Graduate Research Assistant. Later, in November 1999, he was employed by the Agricultural and Biosystems Engineering Department as a full-time research assistant. Prior to graduation, the author was hired by the International Technology Corporation as a GIS analyst.