GUIDANCE DOCUMENT

Archaeological Geophysics for DoD Field Use: A Guide for New and Novice Users

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FORWARD

Preparation of this document was funded by the Environmental Security Technology Certification Program (ESTCP) as part of a project entitled "Streamlined Archaeo-Geophysical Data Processing and Integration for DoD Field Use" (ESTCP Project No. 200611). That project's primary objective is to demonstrate and validate a multi-sensor geophysical approach for detecting and characterizing subsurface deposits at archaeological sites. An important component of the approach is the use of a variety of graphical and mathematical methods to "fuse" or integrate data from a number of sensors into a single image whose total—in terms of information content—is greater than the sum of its parts. The multi-sensor approach and data integration methods were explored by an earlier project (completed in 2006): "New Approaches to the Use and Integration of Multi-Sensor Remote Sensing for Historic Resource Identification and Evaluation (Project CS-1263)". That project, funded by the Strategic Environmental Research and Development Program (SERDP), was executed by a team of researchers at the University of Arkansas at Fayetteville (Dr. Fredrick Limp, Dr. Kenneth Kvamme, and Ms. Eileen Ernenwein) with assistance from ERDC CERL (Dr. Michael Hargrave), NASA (Dr. Tom Sever and Mr. Burgess Howell) and others (Kvamme, et al. 2006).

ESTCP Project 200611 is also developing *ArchaeoMapper*. This new software, presently being developed at the University of Arkansas-Fayetteville (by Dr. Jackson Cothren, Dr. William Johnson, and Ms. Eileen Ernenwein) will serve as the primary vehicle for infusing the multi-sensor approach into use by the Department of Defense, other agencies, research and cultural resource management groups in the US. Developed using Matlab and Java software development programs, *ArchaeoMapper* is a user-friendly software package that provides a broad array of data processing capabilities for highly experienced geophysical practitioners as well as new and novice users.

This guidance document on sensor selection will be useful to individuals who wish to become knowledgeable sponsors of geophysical surveys conducted by specialized consultants as well as to individuals who wish to learn to conduct their own surveys, and those who seek to advance from novice to more sophisticated practitioners. At the time of writing, the first release of ArchaeoMapper is near completion, and will be ready for use at the 2009 National Park Service Remote Sensing workshop.

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1. INTRODUCTION

Geophysics is the study of the Earth by quantitative physical methods (including magnetometry, electrical resistance, conductivity, magnetic susceptibility and ground penetrating radar), which are used to detect, map, and characterize subsurface phenomena including buried archaeological deposits. An effective use of geophysics can improve the reliability, reduce the invasiveness and, in many cases, lower the overall costs of archaeological investigations (Hargrave, et al. 2002; Kvamme, et al. 2006). Despite these potential advantages, the adoption of geophysics by cultural resource management (CRM) practitioners in the United States has been very gradual. One of the reasons for this is the lack of training opportunities. Although there are some very good short courses, such as the annual National Park Service (NPS) workshop and periodic Forest Service ground penetrating radar (GPR) workshops, much more extensive hands-on experience is needed for archaeologists to become informed consumers and eventually practitioners of archaeological geophysics. Furthermore, with only a handful of US universities offering formal training, the level of geophysical expertise of recent graduates of archaeological programs provides little promise for the near future. Additional factors that have contributed to the slow adoption of geophysics by archaeologists in the U.S are the relatively high costs of equipment and the methodological conservatism of CRM practitioners and regulatory agencies (e.g., State Historic Preservation offices) (Hargrave, et al. 2002).

Confronted with the need or desire to conduct a geophysical survey, an archaeologist with little or no familiarity with geophysics is faced with considerable uncertainty regarding what methods and instruments to use, how much time it will take, how much it will cost, and how to collect, process, and interpret the data. Some ability to resolve these questions is necessary even if the goal is simply to work effectively with a geophysical consultant.

A number of published, non-technical volumes explain the basic principles of geophysical methods in archaeology. One of the first widely available overviews was Anthony Clark's *Seeing Beneath the Soil (1990, 1996)*. Clark provided introductory explanations of electrical resistivity, magnetometry, and magnetic susceptibility and, in the revised edition, more limited descriptions of ground-penetrating radar and conductivity. Gaffney and Gater (2003) later provided a similar overview of the main methods, with updates on recent advances in instrumentation and data processing. While these volumes are valuable resources and have made a significant impact to the discipline, they are both written from a British/European perspective, and do not address some of the important issues faced by North American archaeologists (Hargrave, et al. 2002). For example, in North America, the prehistoric archaeological record includes many features that are characterized by (in geophysical terms) a very low-contrast with their surroundings, making them difficult to detect. In the US there is also a greater focus on ground penetrating radar (GPR) and electromagnetic induction (EMI) techniques.

Conyers and Goodman (1997) and, more recently, Conyers (2004) provide in-depth, but still introductory overviews of GPR. Two new volumes have recently been published that together cover the breadth of geophysical methods and applications for North American archaeology. The late Alan Witten finished *Geophysics and Archaeology* (2006) just prior to his sudden death in February 2005. In addition to the commonly employed magnetometry, resistivity, GPR, and EM induction, Witten (2006) provides a solid foundation for the archaeological use of gravity, geotomography, and resistivity tomography. Perhaps the single-most useful addition to the literature for DoD and other CRM practitioners, *Remote Sensing in Archaeology*, edited by Jay K. Johnson (Johnson 2006) provides introductions to the methods that are most commonly used North America: GPR, conductivity, magnetometry, resistivity, and magnetic susceptibility. That volume also has chapters describing the use of geophysics in North American CRM, aerial remote sensing, data processing, the effective use of multiple sensors, and ground truthing. Finally, the most recent advances in methodology and case studies from around the world are presented quarterly in the journal *Archaeological Prospection*, and occasionally in other archaeological and geological journals. For more in-depth theoretical and technical explanations of near-surface geophysical methods, consult Reynolds (1997), Musset and Khan (2000), and Burger et al (2006).

What is most lacking in all of these widely available volumes is detailed guidance to help new users design and conduct a geophysical survey. Clark (1996) provides a graphic depiction of how some of the more common methods should theoretically respond to typical archaeological targets, and Gaffney and Gator (2003) discuss the many factors, including geology, vegetation, and weather, that partially dictate the success of a survey. Similarly, Johnson (2006) opts to discuss the important factors in a narrative covering various aspects of site setting. David (1995) provides guidelines intended for archaeologists and geophysical practitioners working in the UK, including standards for how to conduct a survey and report findings, and how to choose the most suitable geophysical method. Much information is summarized in tables listing the types of features that could be detected by magnetometry, resistivity, conductivity, and GPR, the effects of local geology on magnetometry, and a questionnaire designed to determine the suitability of each method for a given archaeological setting. In a similar effort, Hargrave (2007) provides guidance on selecting geophysical techniques that are appropriate for use at sites in North America. This work was intended for those with little or no previous experience and cautions beginners against doing geophysical surveys at unpromising sites. An earlier effort by Somers and Hargrave (2003) included guidance documents and a software tool (ATAGS) to help users select appropriate instrument configurations, sampling strategies, and field techniques. This effort was limited, however, to magnetometry and resistivity and excluded other commonly used methods such as ground penetrating radar, conductivity, and magnetic susceptibility. The guidance documents by David (1995), Hargrave (2007), and Somers et al. (2003), while still readily available, have not yet achieved wide circulation in the U.S. There is still a great need for guidance that covers all of the widely used geophysical methods and how to use them at North American archaeological sites.

Kvamme et al. (2006) have recently provided a detailed report on the results of an ambitious, multi-faceted project funded by the Strategic Environmental Research and Development Program (SERDP). That effort focused, among other things, on alternative approaches to data fusion, that is, graphical and numerical approaches to integrating the results of surveys using multiple sensors. Kvamme et al. (2006) also report on what is probably the most systematic approach to the field verification (ground truthing) of geophysical interpretations and predictions yet conducted in the US.

This document was created as part of a project entitled *Streamlined Archaeo-geophysical Data Processing and Integration for DoD Field Use* (funded by the Environmental Security Technology Certification Program, Project 200611), which was designed to demonstrate and validate the multi-sensor approach to archaeological site evaluation—including a number of methods for data integration that were investigated during the previously discussed SERDP project (Kvamme, et al. 2006). This ESTCP project will provide resources needed to allow DoD CRM personnel to make effective use of a multi-sensor geophysical approach to the evaluation of archaeological sites. Components of the project include: (1) development of a user-friendly software package (*ArchaeoMapper*) for the processing, display, integration, and interpretation of data from all of the commonly used geophysical methods; (2) demonstrating field and processing methodologies to DoD personnel; and (3) creating and disseminating guidance (via this document) to assist DoD CRM professionals, archaeological consultants providing services to DoD, and the general archaeological community in the process of designing, conducting, and understanding a geophysical survey. The development of *ArchaeoMapper* software is currently underway, scheduled for completion in May 2009. *ArchaeoMapper* will be demonstrated and evaluated by a team of DoD and civilian users in 2009-2010.

This document provides step-by-step guidance for (1) estimating the suitability of a site for geophysical survey, (2) determining which geophysical methods or combination of methods have the greatest potential for success, (3) determining which particular instruments or types of instruments to rent or buy, (4) designing a data collection strategy, and (5) estimating the time that will be needed for data collection fieldwork and subsequent processing. In addition, we propose (6) a strategy to aid archaeologists in understanding the geophysical characteristics of sites in a particular area of interest, such as a DoD installation. We have designed this document not only to guide beginners through their first surveys, but to help novice users develop a better understanding of geophysical methods and to improve their field techniques. Guidance for data processing and interpretation will be provided in the *ArchaeoMapper* user's manual. Together these documents offer comprehensive guidance in archaeological geophysics for a broad spectrum of the US archaeological community.

2. REVIEW OF GEOPHYSICAL METHODS IN ARCHAEOLOGY

2.1 Brief History of Geophysics

Although many archaeologists in the United States still view the use of geophysical techniques as "high-tech," none of the methods discussed in this document are new. The first systematic geophysical survey on a U.S. archaeological site was conducted at Williamsburg, VA, in 1938. Mark Malamphy used equipotential (a method that is not widely used) to search for a stone vault suspected to be associated with an early church. A promising anomalous area was identified, but excavation revealed no archaeological features. The area was resurveyed some 50 years later and subsequent ground truthing suggested that the geophysical anomaly was associated with differential leaching of small fossil shells (Bevan 2000; Gaffney and Gater 2003).

Electrical resistance was first used at an archaeological site in 1946 by Richard Atkinson. With a Megger Earth Tester (then widely used in civil engineering) and a switching system of his own design, Atkinson was able to detect moist, silt-filled ditches that had been excavated into dry natural gravel at Dorchester-on-Thames, UK (Atkinson 1953; Clark 1996; Gaffney and Gater 2003). In the United States, Christopher Carr (Carr 1982) was an early advocate for the use of resistance survey in archaeological research.

Another milestone application of geophysics occurred in 1958, when Martin Aitken used a proton magnetometer to detect an early kiln near Peterborough, UK (Aitken 1958, 1974; Gaffney and Gater 2003). Aitken also detected earth-filled pits — a capability that would have important implications for the widespread use of magnetic techniques in the United States.

During the 1970s, geophysics began to be integrated into archaeology in Great Britain and parts of Europe. Roman and late prehistoric sites in those areas often include metal artifacts, stone and masonry architecture, and fired clay roofing tiles. Such materials contrast sharply with their surroundings and could be identified in pre-computer era maps that were characterized by relatively few, widely spaced data points (Hargrave, et al. 2002; Isaacson, et al. 1999; Scollar, et al. 1990).

John Weymouth and Bruce Bevan (Bevan 1977, 1983; Bevan and Kenyon 1975)conducted a number of early surveys in the United States (Bevan 1977, 1983; Bevan and Kenyon 1975; Weymouth 1976, 1985, 1986; Weymouth and Nickel 1977; Weymouth and Woods 1984) that demonstrated the usefulness of geophysics, particularly at sites characterized by relatively high-contrast features. In the United States, however, the single-most common type of prehistoric feature is the earth-filled pit. Ferrous metal artifacts are absent in the prehistoric record and stone architecture is found only in limited areas. It was not until the revolution in information technology (e.g. fast computer processors and mapping/GIS software) allowed the collection, processing, and mapping of thousands of data values that relatively subtle features like earth-filled pits could consistently be detected in magnetic surveys (Hargrave, et al. 2002; Kvamme 2001).

Ground penetrating radar (GPR) was a somewhat later addition to the geophysical arsenal. GPR was initially developed to locate subsurface cavities such as mine shafts and tunnels. It was quickly adopted by geology, civil engineering, and many other disciplines (Conyers and Goodman 1997). In 1975, one of the first archaeological applications of GPR was an effort to map buried walls at Chaco Canyon, NM (Vickers, et al. 1976). Other early U.S. GPR surveys focused on historic features such as cellars and buried stone walls (Bevan and Kenyon 1975; Kenyon 1977). Use of GPR in the United States continued through the 1980s and 1990s, demonstrating the technique's potential for detecting a wide variety of feature types (Conyers and Goodman 1997).

Although geophysics is not yet thoroughly integrated into CRM in the United States, it is being used more frequently than ever before (Johnson 2006; Kvamme 2001, 2003; Kvamme, et al. 2006; Silliman, et al. 2000). A number of large area surveys — many of them unpublished but reported at professional conferences — have demonstrated geophysics' potential contributions to archaeological investigations of late prehistoric and historic occupations (Butler, et al. 2004; Clay 2001; Hargrave 2004; Hargrave, et al. 2004; Hargrave, et al. 2002; NADAG 2007; Peterson 2003). Geophysics is now an area of specialization in archaeological graduate programs at a handful of universities (e.g., University of Mississippi-Oxford, University of Arkansas-Fayetteville), and in-house geophysical capabilities exist at university-affiliated research units such as the Arkansas Archaeological Survey, Glenn Black Laboratory at Indiana University-Bloomington, and Indiana University and Purdue University-Fort Wayne. Federal agencies including the National Park Service (Midwestern Archaeological Center), U.S. Army Corps of Engineers (Engineer Research and Development Center, Construction Engineering Research Laboratory; the Vicksburg, Mobile, Savannah, and New England Districts), and some Army installations (Fort Riley, KS; Fort Drum, NY) have in-house geophysical capabilities. A number of small geophysical consulting firms focus almost exclusively on archaeological applications.

Trends calling for an increased use of geophysics by U.S. archaeologists in the future include the gradually increasing labor costs of hand excavation (with no corresponding increase in rates of excavation), versus significant improvements in the performance of geophysical instruments relative to their cost (Kvamme 2001). Social and legislative changes in CRM, including an increased role for Native American groups in the management of prehistoric cultural resources on tribal and federal lands, suggest the need for noninvasive or, at least, minimally invasive approaches for evaluating the NRHP eligibility status of some sites. On balance, CRM personnel in the DoD, other federal and state agencies, and the private sector will find it increasingly useful to be aware of the potential benefits — and the limitations — of geophysical techniques.

2.2 Fundamental Concepts in Archaeological Geophysics

Archaeological geophysics involves the measurement of certain physical properties in the near-surface of the earth in order to detect and characterize buried archaeological features. The near-surface in archaeological contexts refers to the uppermost 1-2 m (Kvamme 2001). Both active and passive methods are employed.

Active methods generate their own signals, such as electromagnetic fields or electrical currents, and measure the earth's response. Passive methods, on the other hand, utilize naturally occurring signals and simply "listen" for responses from the near surface (Heimmer and De Vore 1995). Magnetometry, which utilizes the earth's magnetic field, is the only passive method described in this volume. Ground penetrating radar, resistivity, and EMI are all active methods.

Geophysical data (measurements of selected geophysical properties at particular points on or very near the ground) are collected by moving an instrument across the landscape, most often in evenly spaced parallel transects. These measurements, usually in xyz format (where x,y give the location coordinates and z is the geophysical measurement) are then compiled into a database and displayed to create contour maps or images portraying the spatial variation in the measured properties. A common display method is a raster image, where each individual cell or pixel in the image represents one geophysical measurement.

All geophysical methods rely on differences, or contrast, between archaeological features and their immediate surroundings (background or matrix) (Kvamme 2001). Contrast is the degree to which the geophysical properties of an archaeological feature differ from that of the surrounding soils or sediments (Somers, et al. 2003). This is an important concept, because it implies that the magnitude of a geophysical measurement is not as important as is the amount of contrast it has with the surrounding materials. In other words, an extremely electrically resistive archaeological feature will not be detected if the surrounding matrix is equally resistive. When contrast is sufficient, however, an anomaly is produced. Anomalies are areas in a geophysical data set that contrast with surrounding measurements, and are called "anomalies" until they can be otherwise identified (Kvamme 2001). Geophysical data often encompass a range of values from negative to positive. Anomalies can thus be either positive, negative, or dipolar (having both a positive and negative component). All of these anomaly types can indicate cultural features.

A geophysical survey of an archaeological site is successful if it can identify and characterize buried archaeological features, but many factors besides archaeology contribute to variation in the data. Geophysical measurements unfortunately have some degree of "noise" associated with them. Noise in geophysical data includes anything that is not representative of what lies on or beneath the surface. Examples of noise are data spikes (extremely high or low, often solitary readings, usually surrounded by valid measurements) and other random or periodic errors related to instrument operation (Hargrave 2007; Somers, et al. 2003). It also includes patterned interference, such as radio waves and magnetic storms. Noise becomes a problem when it obscures archaeological features, which can easily occur if the contrast between noise and the background is greater than the contrast provided by archaeological features. Fortunately there are many ways to filter noise out of the recorded signal, either by avoiding certain areas or times of day for data collection, or with post-acquisition data processing.

Another problem with the recorded data is the prevalence of unwanted signals (electromagnetic fields, electrical currents, or other physical signals that are recorded by

geophysical instruments). It is useful to think of the recorded signal as several signals added together. The signal of interest is from archaeological features, but there are also signals from other subsurface phenomena such as tree roots, rodent burrows, buried utilities, sedimentary layers, and rocks. These unwanted signals that are unrelated to the archaeological record are called clutter (Hargrave 2007; Somers, et al. 2003). Anomalies arising from clutter become a problem when they cannot be differentiated from anomalies related to archaeological features. Some anomalies can be clearly identified as representing cultural features because they exhibit diagnostic patterns such as circular or rectangular house floors. Smaller and less patterned archaeological features, however, produce anomalies that are very difficult to distinguish from clutter anomalies.

The ability to detect subsurface features is also limited by data density and resolution. Data density (also called sampling density) is the number of geophysical measurements recorded per unit area (Somers, et al. 2003), or per unit volume in the case of three dimensional methods such as GPR. It is dictated by the sampling interval (distance between measurements along the data collection lines, transects, or traverses) as well as the distance between lines. Many contemporary geophysical surveys are done with a sampling interval of .5 to .125 per meter, with lines spaced 1 to .5 m apart. Resolution of smaller and lower contrast features is improved by increasing the data density. Clark (1996) shows that as the sampling interval is decreased from 1.5 to .125 m, the ability to differentiate a kiln from a piece of iron on the surface is increased (using a magnetometer). The experiment shows that .5 m is the largest suitable interval, and there is a considerable improvement at .25 m, but only marginal improvements at .125 m. Using a .25 m or smaller sampling interval along transects is easily accomplished with today's geophysical instruments, with the main limit on data density being the spacing between lines. Both Clark (1996) and Gaffney and Gater (2003) suggest that 1 m between lines is adequate for most geophysical surveys in the UK (assuming sampling intervals of at most .5 m along transects but usually .25 or less), although the latter suggest .5 m should be used for research level surveys. In North America it is more common to use .5 m line spacing, with 1 m spacing reserved for sites with very large high-contrast features. In some cases .25 m lines spacing is used, particularly with small-area GPR surveys where the principal targets are small and low contrast.

A final factor to consider is the size of target features. Though contrast is the overriding factor, size plays an important role in the detection and recognition of cultural features. If two features are composed of identical materials and are buried at equal depths in the same sediment matrix, the larger of the two will be more easily detected and identified as a potential cultural feature for a number of reasons. First, the smaller feature is less likely to be directly below or close to transect lines, so the recorded signal would be relatively weak. Second, the smaller feature will produce a smaller anomaly, perhaps represented by only one measurement (one pixel). Anomalous readings recorded in only one pixel are easily mistaken for data spikes (errors) and usually removed during data processing. Finally, the anomaly from a smaller feature is less likely to take an identifiable shape (square, linear, or circular), making it

more difficult to distinguish from noise and clutter. For a feature to be reliably detected it should therefore be recorded by at least two passes of the instrument (Kvamme 2003). In summary, when all other factors are equal, the likelihood of detecting and recognizing small archaeological features is improved as sampling density is increased.

2.3 Geophysical Methods

A variety of geophysical methods are applicable to the investigation of archaeological sites. The most widely used methods in the U.S. are magnetometry, electrical resistance, conductivity, and ground penetrating radar (GPR) (Bevan 1998; Clark 1996; Gaffney and Gater 2003; Heimmer and De Vore 1995; Kvamme 2001; Scollar, et al. 1990). Another method, magnetic susceptibility (MS), has been sporadically used for decades but is not routinely employed in the U.S. Recent applications of MS, however, show that this method should receive more emphasis in archaeological geophysics (Dalan 2006; Kvamme, et al. 2006). Other methods such as gravity (Gaffney and Gater 2003; Witten 2006), seismic (Clark 1996; Gaffney and Gater 2003), geotomography (Witten 2006), thermal (Clark 1996; Gaffney and Gater 2003), induced polarization (Clark 1996; Gaffney and Gater 2003), self potential (Gaffney and Gater 2003), and phosphate analysis (Clark 1996; Gaffney and Gater 2003), are not commonly used in archaeology and are therefore not covered here.

The remainder of this chapter provides a brief explanation of the main geophysical methods used in archaeology today. Each method is described by addressing the following questions:

(1) ***What* property is measured?** In other words, what fundamental geophysical property is being exploited so that archaeological features or deposits and other subsurface phenomena can be detected?

(2) ***How* is the property measured?** This section includes the theoretical background that explains how geophysical properties are measured.

(3) **How is the instrument *configured* for data collection?** Many different geophysical sensors are available for each method, and some can be set up in different ways depending on field conditions and the goals of the survey. Typical configurations are described.

(4) **What are the instrument's limits in terms of *depth* and *resolution*?**

(5) **What are the method's *advantages* and *disadvantages*?** The pros and cons of the method are briefly discussed.

2.3.1 Electrical Resistance

Property Measured. Electrical resistance is the degree to which a material restricts the passage of an electric current, and is measured in Ohms (Clark 1996; Gaffney and Gater 2003; Somers 2006). Variation in electrical resistance is almost entirely dictated by the amount of moisture in the soil. Coarse grained, well-drained soils (gravels, sands) exhibit a relatively high resistance, whereas fine grained soils (clays, silts) that hold more moisture exhibit lower resistance. Compared to soil, rocks and bricks are typically

characterized by very high resistance. Electrical resistance is useful on archaeological sites because cultural features represent localized disturbances to natural soil strata, and often include concentrations of organic materials, rocks, and other artifacts. These disruptions to the natural soils are associated with a localized contrast in moisture retention and therefore electrical resistance. A wall made of rock or brick, for example, is typically much more resistive than surrounding soils.

Method of Measurement. There is only one way to directly measure electrical resistance: pass a current through the material and measure it with a voltmeter. If the current (I) is kept constant and the voltage (V) is measured, resistance (R) can be calculated using Ohm's Law:

$$R = V/I$$

Some instruments take an additional step to convert resistance to apparent resistivity, but this is not usually necessary for typical archaeological applications. For more details see Clark (1996) or Gaffney and Gater (2003).

Although the galvanic (direct-contact) method is the only true way to measure resistance, it can be *approximated* by measuring electrical conductivity with electromagnetic induction (EMI). Since conductivity is the theoretical inverse of resistivity, one can simply invert the conductivity measurements. In practice, however, the relationship is not always so simple. In some cases, when the two data sets are compared they are very highly correlated. The conductivity and resistivity images shown in Figure 1a-b are strongly correlated ($r = .71$). Yet in other cases, such as the conductivity and resistivity data from Army City (Figure 1c-d), the two datasets are statistically independent ($r = .14$). The discrepancy is related to differences in depth sensitivity, resolution, and the method of measurement (described in the next section). This is an important consideration when deciding between EMI and electrical resistance for a particular survey. In the authors' experiences, sometimes resistance is better able to resolve discrete features (though this needs further testing), but EMI can be done faster and is more flexible with respect to field and weather conditions because it does not require direct contact with the ground.

Configurations. Electrical resistance is measured by inserting electrodes into the ground and measuring the resistance between them. A great variety of probe configurations can be used (see Clark 1996; Gaffney and Gater 2003). By far the most common and practical for archaeology is the twin probe array (Figures 2-3), developed in Switzerland in the 1960s (Schwarz 1961) and further developed for archaeology in Britain by Aspinall and Lynam (1970). Though there are some disadvantages to the twin probe array compared to others (see Gaffney and Gater 2003), it remains a standard in archaeological geophysics (Clark 1996). The twin probe array utilizes a pair of mobile probes (usually mounted on a frame) and a remote pair of probes located far enough away (at least 30 times the distance between mobile probes) that they do not disproportionally influence the resistance within the area to be surveyed (Figure 3) (Clark 1996). At each measurement position, a weak electrical current is introduced into

the ground from one mobile to one remote probe, and the voltage is measured by the adjacent mobile probe. As the instrument is moved along, data are only logged when the mobile probes are inserted into the ground. The need to insert probes into the ground makes resistance survey more labor intensive than other geophysical methods, and results in a lower data density and spatial resolution. One way to improve survey speed is to use multiple pairs of probes on one frame. Geoscan Research Ltd (UK) has done this with their MPX multiplexer attachment, which extends the basic RM15 instrument frame out to as many as five probes and effectively makes four mobile probe pairs (Figure 2b). Each time the probes are inserted into the ground, the multiplexer alternates the probes so that a series of four measurements are taken along the array. This quadruples the number of data points collected each time the instrument is repositioned, making survey considerably more efficient.

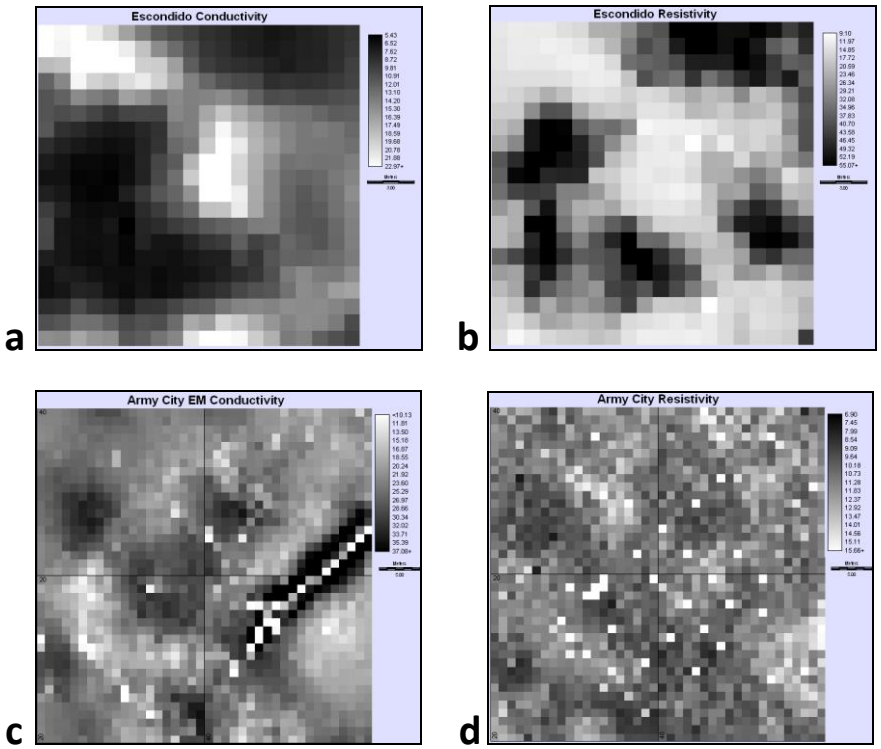


Figure 1. Relationship between galvanic electrical resistance and EMI conductivity. (a) EMI conductivity data from a 20 x 20 m area at Pueblo Escondido; (b) galvanic electrical resistance from the same 20 x 20 m area; (c) EMI conductivity data from a 40 x 40 m area at Army City; (d) galvanic electrical resistance from the same area. Note that the resistance images (b & d) are shown in a reversed grayscale for easier comparison with conductivity.

a **b**

Figure 2. Commonly used resistance instruments and configurations: (a) TR/CIA resistance meter using .50-m twin probe array; (b) Geoscan RM-15 with MPX multiplexer using .50-m twin probe array.

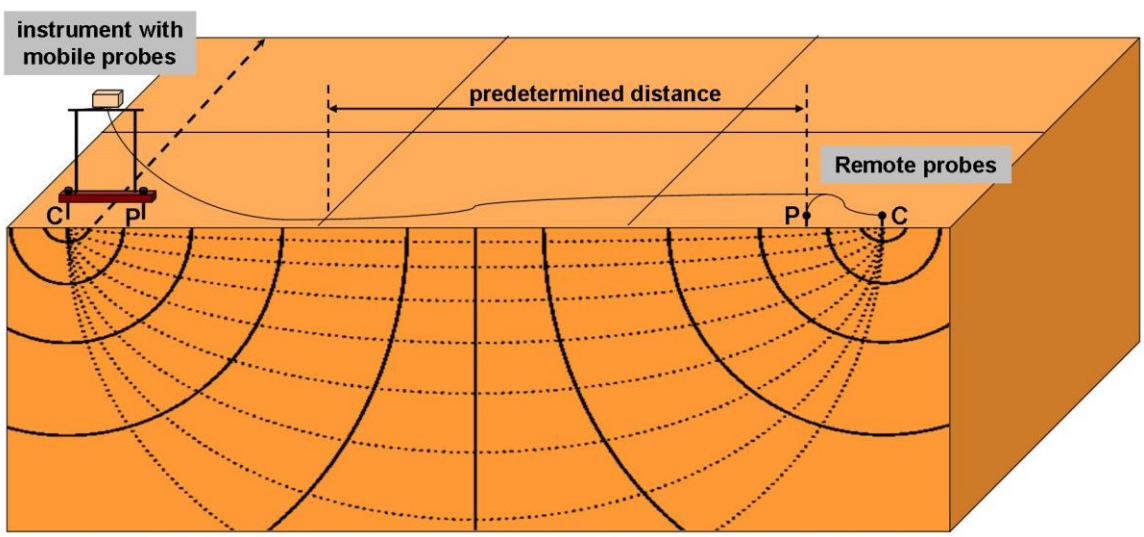


Figure 3. Illustration of the twin probe array and theoretical uniform ground currents. The distance between the mobile and remote probes must always be equal to or greater than 30 times the distance between mobile probes. This distance is kept between the remote probes and the closest edge of the area being surveyed. Not drawn to scale.

Depth and Resolution. The depth and resolution of resistance data are dictated by the probe separation and sampling density. Generally speaking, as the probes in a resistance array are moved farther apart, the depth sensitivity increases (Gaffney and Gater 2003). With the twin probe array the measurement is most sensitive to the depth equal to the mobile probe separation (Somers 2006). Using .5 m mobile probe separation, for example, the depth of measurement is centered at about .5 m, but also includes areas immediately above and below this depth (in other words, each pixel or measurement represents the resistivity of a three-dimensional region of the subsurface,

whose center is roughly .5 m below the ground surface). Increasing the probe separation also has the unwanted effect of lowering spatial resolution. This is because the wider probe separation means that a greater volume of earth is measured, so the volume of a feature represents a smaller percentage of the sampled volume, making detection less likely. For example, a small pit feature near the surface might constitute over half the total volume of the area being measured with .5 m probe separation, but the same pit buried 1 m deep would make up a much smaller proportion of the total volume measured with 1 m probe separation and might not be detected at all. This idea is explored in more detail in the next section.

Typical survey speed with resistance meters is relatively slow compared to other methods, so data densities are low (usually 1 to 4 measurements per square meter). This places a practical limit on resolution, such that lower contrast and smaller features are difficult to detect unless considerable time is taken to increase the data density. A general rule of thumb is that the distance between measurements should be at most half the size of the smallest feature to be detected. If this is done, the smallest features will be recorded in at least two locations, so they are less likely to be interpreted as data spikes (erroneous measurements). Sampling density can be increased in the survey direction (along survey transects) by taking more measurements per meter, and this is often done. For small features, particularly graves, lines spaced less than .5 m apart can be used (though this slows and complicates survey to some degree).

Advantages and Disadvantages. In addition to the lack of speed and corresponding low resolution, electrical resistance is adversely affected by variations in soil moisture. Survey results are less likely to be reliable when the soil is extremely dry or highly saturated (Clark 1996; Kvamme 2001). Under normal conditions (neither extremely wet or dry), however, resistance instruments are very well-suited for detection of larger features based on contrasts in soil type. Examples include ditches, trenches, house basins, mounds, and historic architectural remains. Electrical resistance offers several advantages over most other methods. It is perhaps the most widely applicable technique. By altering the spacing between the mobile probes one can, to some extent, control the depth of survey. Another important advantage of electrical resistance is that it is not influenced by metallic objects, and so can be used at sites that are littered with metallic debris such as trash from construction, military training, picnickers, or metal pin flags from previous archaeological projects (Kvamme 2001). Most other methods, most notably magnetometry but also EMI, are adversely affected by non-archaeological metal debris.

2.3.2 Electrical Conductivity

Property Measured. Electrical conductivity is a measure of how easily an electrical current will flow through a material (Witten 2006), measured in Siemens or milliSiemens (mS). A Siemen is the inverse of an Ohm, or equal to 1/Ohm. Older references use the equivalent unit “Mho”, which is simply “Ohm” spelled backwards. It is the theoretical inverse of resistivity, but as discussed earlier, conductivity data are often not comparable to the resistance measurements taken with probe-array systems (see

section 2.3.1). By convention, when archaeologists talk about resistivity or resistance, they are usually referring to data collected with an instrument that uses probes inserted into the ground (Figure 2). When we talk about conductivity, we are almost always referring to measurements taken with the electromagnetic induction (EMI) method (Figure 4). Conductivity maps tend to resemble maps of resistance data and can be interpreted using the same principles, although the resolution of conductivity data is sometimes poorer due to differences in depth sensitivities. Despite the fact that EMI data are often collected at a higher density than resistance data, EMI measurements are usually influenced by a greater volume of ground, potentially blurring anomaly boundaries. Like resistance, conductivity is an excellent method for detecting anomalies that are based on contrasts in ground moisture or material type. Small pits are not easily detected, but larger pit features, ditches, and the plowed-down remains of earthworks can be detected very effectively.

a **b**

Figure 4. Commonly used electromagnetic induction (EMI) instruments: (a) Geonics EM31; (b) Geonics EM38.

Method of Measurement. The EMI method of measuring conductivity is considerably more complex than resistance, so only the fundamental principles are explained here (for more detailed explanations see Mussett and Khan 2000; Reynolds 1997; Witten 2006). When an electrical current is passed through a coil or loop, an electromagnetic field is created (Witten 2006). If this EM field is close enough to objects that are somewhat conductive, then the field will cause currents to flow in them. Just as the electrical current in the coil created an EM field, the currents in the objects will create EM fields. This process is called induction. In archaeological surveys, EMI conductivity data are usually collected with two coils, one transmitter and one receiver in a configuration that has many names, including Slingram, horizontal loop, moving transmitter-plus-receiver, moving-source dual-coil, and ground-conductivity meter (Mussett and Khan 2000; Reynolds 1997). The transmitter creates an EM field called the primary field that extends in all directions, but most importantly into the ground. If the ground is conductive, or contains deposits that are conductive, currents will flow in them in response to the primary field. These newly created currents, called eddy

currents (because they form like eddies in the bend of a river), will in turn create a secondary EM field (Witten 2006). The secondary and primary fields are measured by the receiver coil (Figure 5).

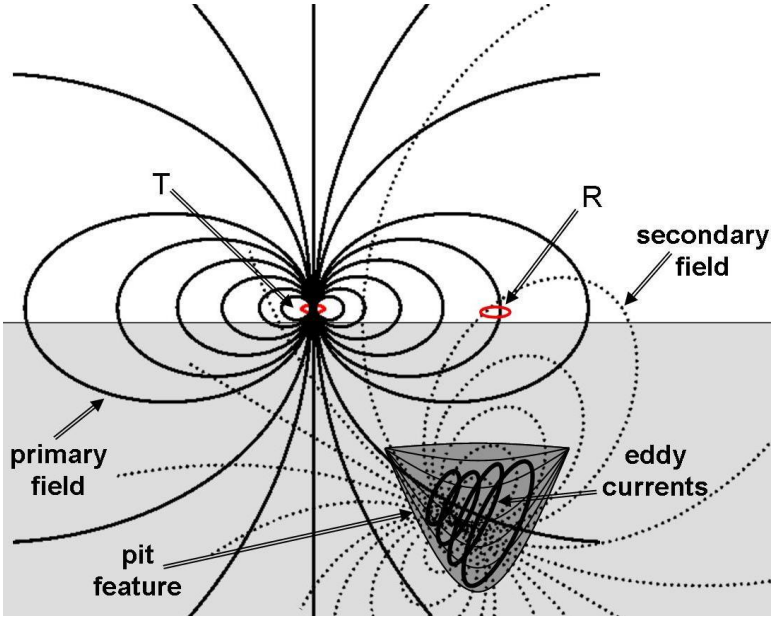


Figure 5. Electromagnetic Induction model: the transmitter coil (T) creates a primary EM field extending in all directions. This causes eddy currents to flow in conductive objects such as the pit feature shown here. The eddy currents in turn create a secondary field. Both the primary and secondary fields are measured at the receiver coil (R).

Conductivity is approximated by comparing the secondary to the primary field, and measuring the phase lag. Phase is a term used to describe the relative temporal positions of two wave signals. If two waves are in phase, they are time synchronous. If out-of-phase, there is some lag between them. There is a finite amount of time that it takes for the induction process to occur and the secondary field to be received. The higher the ground conductivity, the greater is the lag of the secondary field (Mussett and Khan 2000; Reynolds 1997). This lag is measured by mathematically decomposing the received signal into two parts: in-phase and out-of-phase. The in-phase component is forced to be in phase with the transmitter (primary field), while the out-of-phase (quadrature) component is set to lag by 90 degrees. The signal can always be split in this way by varying their amplitudes so that they add up to the original signal (Mussett and Khan 2000). For instruments operating at what is called a low induction number, the magnitude of the quadrature component of the secondary field is proportional to the apparent conductivity (Mussett and Khan 2000). The in-phase component is in turn used to calculate MS, which will be discussed in section 2.3.3.

Configuration. There are several ways to configure EMI instruments, by using variations in frequency, number of coils, coil spacing, and coil orientation. Only those

commonly used in archaeology are discussed here. The most common and practical configuration is to mount one transmitter coil and one receiver coil on opposite ends of a boom (Figure 4). Since the transmitter and receiver need to be a specific distance apart for each measurement (McNeill 1996), using the boom makes it much easier and faster to collect data while moving along a traverse . According to McNeill (1996), for any given coil spacing there is an optimum frequency. Frequencies above or below the optimum do induce secondary fields, but if the coil spacing is too small or too large the receiver will not adequately record them. To the contrary, Won et al. (1996) maintain that coil spacing and frequency *can* be set independently. Instruments have been designed on this principle and usually have fixed coil spacings, but use multiple frequencies set by the operator. The idea is that each frequency will penetrate to a different depth so multiple frequencies can be used to simultaneously record data at many depths. It is unclear if the fixed-coil, multifrequency instruments are adequate for archaeology, but field tests conducted by the lead author (Ernenwein 2002) have shown that when the frequency and coil spacing are matched as suggested by McNeill (1996), results are much better than if multiple frequencies are used. These studies also suggest that data from single frequency, fixed-coil instruments are generally less noisy and resolve features significantly better than multifrequency instruments. In another field experiment by the lead author at Tiwanaku (Bolivia), the GEM-2 (Geophex) was unsuccessful, while the EM38 (Geonics, Ltd.) produced very good results. Additional tests of these instruments are needed, however.

Another configuration sometimes used in archaeology involves the use of a dipole transmitter and a second dipole receiver that are connected by a cable and dragged along the ground. This configuration is the basis of the *OhmMapper*, manufactured by Geometrics, Inc. (CA). Though it looks very different than most EMI instruments, the *OhmMapper* operates in much the same way. It actually measures conductivity with the electromagnetic induction (EMI) method and converts it to resistivity, and is marketed as a resistivity instrument.

Depth and Resolution. The depth and resolution of conductivity data measured with EMI depend on a number of factors, most notably frequency, sensor height above the ground, and coil orientation. First consider frequency. Lower frequency EM fields have longer wavelengths, and are therefore able to penetrate deeper into the ground (Witten 2006). In a general sense depth sensitivity, called the skin depth, is greater for lower frequencies. The drawback of lower frequencies, however, is that a greater volume of earth is factored into the overall measurement, therefore small objects such as archaeological features may not be detected. It is better to use a higher frequency, which will have lesser skin depth, so that the archaeological features make up the maximum percent of the total volume being measured. In other words, higher frequencies allow greater spatial resolution, or ability to detect smaller features, but lower frequencies may allow detection of relatively large or high contrast targets that are too deep to otherwise be detected (Witten 2006) (Figure 6). Though shallow objects may be adequately detected with a relatively low frequency (Figure 6b), higher frequencies are usually best for detecting typical archaeological features. It is therefore

no surprise that the Geonics EM38 is so often used (Clay 2006), and lower frequency instruments such as the EM31 are used for deeper and larger targets (e.g. Dalan 1991).

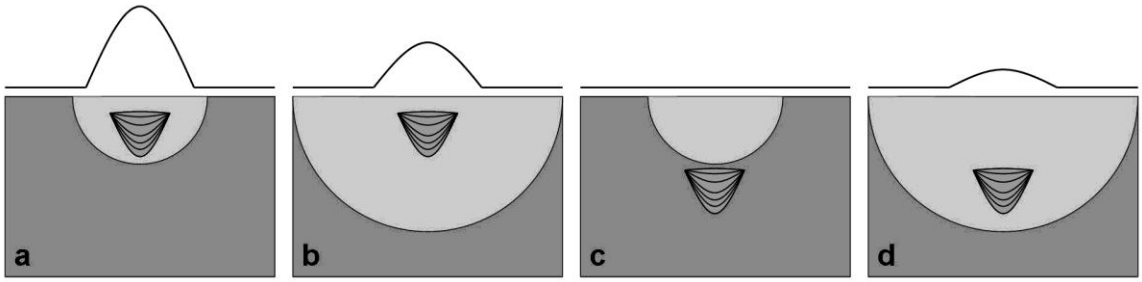


Figure 6. Effect of EMI frequency and target depth. The line plots represent the relative magnitude of conductivity measurements and the plots below represent cross sections of a pit feature buried at different depths. Half-circles show the limits of depth penetration due to frequency. The best possible scenario is to have (a) a shallow feature measured at a relatively high frequency. If the same feature is measured with a lower frequency (b), a larger area is factored into the measurement and a smaller magnitude anomaly is recorded. When deeper features are the target, however, a higher frequency (c) may not penetrate deep enough into the ground, so the feature would not be detected. The best approach for features that are known to be deep is therefore to use a lower frequency (d).

The height of the instrument above the ground is also a major factor affecting depth sensitivity. As the distance between the receiver coil and objects increases, the response from that object diminishes. Beyond the maximum skin depth the return signal from an object is too small to be detected (McNeill 1986). Depth sensitivity can therefore be increased by carrying the instrument as close to the ground surface as possible (Figure 4b). This is especially important when using high frequency instruments such as the EM38 because the skin depth is more limited.

Another important factor affecting skin depth is the orientation of the coils. The two most common orientations are to hold the coils either horizontal or vertical with respect to the ground surface (Reynolds 1997). If the two coils are placed horizontal to the ground surface (imagine two donuts lying on the ground) their orientation is called horizontal co-planar. In this position the horizontal transmitter coil generates a magnetic field whose lines of flux emanate vertically, which also gives this orientation the name vertical magnetic dipole (or simply “vertical mode”). In this position there is maximum energy penetration into the ground (Witten 2006) (Figure 5). This is the most common orientation for most archaeological surveys. When the coils are held vertically with respect to the ground surface, the orientation is called vertical co-planar and the magnetic flux emanating from the transmitting coil is horizontal, called the horizontal magnetic dipole orientation (“horizontal mode”). In this position a much smaller portion of the induced electromagnetic field penetrates the ground so depth penetration is reduced (Witten 2006).

Advantages and Disadvantages. There are many advantages as well as disadvantages to conductivity survey. Compared to resistivity, EMI data can be collected more quickly because there is no need to insert probes into the ground or to occasionally reposition remote probes. Also, EMI data can be collected in areas with very dry or hard terrain, where probes either cannot be inserted, or the current will not flow because of lack of surface moisture. Very dry surface conditions are not necessarily an indication that subsurface conditions are too dry to provide enough contrast—often adequate ground moisture lies only a few centimeters beyond the reach of resistance probes. EMI instruments can also be packed and shipped more easily owing to their smaller size. Additionally, EMI instruments are available for short term rental, whereas resistivity instruments are not. Disadvantages of conductivity surveys include the EM38's sensitivity to electrical interference (e.g., lighting, power lines) and metal debris (Bevan 1998; Clark 1996; Clay 2006). In certain cases, however, the EM38's sensitivity to metal is an advantage, such as with battlefield or other sites where metal artifacts are among the target features (Bevan 1998; Heckman 2005). There is also a problem with thermal drift in many EM instruments, which makes data processing more time consuming than with resistance or magnetometry (Clay 2006). Finally, EMI instruments require relatively frequent and laborious tuning whereas the widely used resistivity instruments, after initial setup, require no "tuning" beyond the occasional repositioning of remote probes.

2.2.3 Magnetic Susceptibility

Property Measured. Magnetic Susceptibility (MS) is a measure of the ability of a material to become magnetized in the presence of a magnetic field (Clark 1996; Dalan 2006). It can be quantified per unit volume (κ) or as a mass normalized susceptibility (χ) (Dalan 2006), but when measured with the EM38 or similar instruments measurements are given as the ratio of the primary to the secondary field in parts per thousand (ppt). All atoms have their own magnetic fields owing to their orbiting electrons, so all substances react (are susceptible) to nearby magnetic fields to some degree (Clark 1996). Dalan (Dalan 2006) describes the different ways that the MS of materials is enhanced. The natural formation of soils involves the conversion of weakly magnetic oxides and hydroxides to more strongly magnetic forms, so topsoil is much more magnetic than subsoil layers. In addition, human activities further enhance topsoil so that soils at archaeological sites are often more magnetic than those in surrounding non-cultural areas. Humans enhance pedogenic processes and therefore susceptibility contrasts by increasing organic matter and altering the porosity of soils, and also by increasing the soil temperature through firing. They may also integrate burned or high-susceptibility materials into the ground. Burning, whether natural or human-caused, also enhances MS (Dalan 2006). The principle types of features that can be detected with an MS survey are therefore burned features, and those involving the displacement of soil. Human magnetic enhancement of topsoil often increases the susceptibility contrast at archaeological sites, thereby increasing the ability to detect human-created features (Clark 1996; Dalan 2006).

Method of Measurement. There are several ways to measure MS, but all rely on the fundamental principle of electromagnetic induction (EMI). Recall from the previous section that a secondary electromagnetic (EM) field can be induced in the ground by creating a primary EM field nearby. Not only does the secondary field contain information about the electrical properties of the ground, it also responds to magnetic properties. Also recall that when the secondary field is transformed mathematically into in-phase and out-of-phase components, the magnitude of the out-of-phase portion is proportional to the ground conductivity. As long as there are no extremely conductive targets in the ground (such as large metallic objects), the in-phase component is considered a measure of MS (McNeill 1986). It follows that some EMI instruments can measure both apparent conductivity and MS simultaneously. Other instruments are designed to measure only MS, but they still use electromagnetic induction.

Configurations. Magnetic susceptibility data are collected in a variety of ways, including relatively high data density horizontal coverage of potentially large surface areas, analyses of soil samples taken at variable intervals across the surface or down an excavation profile, and down-hole measurements taken as a sensor is lowered down a bore hole. For surface surveys, there are two common sensor configurations: single- and dual-coils. Single coil (also called single loop or coincident loop) instruments induce an electromagnetic field into the ground, and measure the frequency of the secondary field. The frequency change is proportional to the average MS of the soil within the vicinity of the coil (Clark 1996). This method requires that the sensor be in direct contact with the soil surface. When two coils are used (Slingram configuration, one transmitter and one receiver; Figure 4), measurements are made by the in-phase response, as described earlier. Both single- and dual- coil configurations are also used in sensors designed for laboratory measurements. Though more time consuming and generally less informative of detailed spatial patterns (due to their very low data density), lab measurements offer a number of advantages. If desired the samples can be dried and put through a sieve, so measurements are no longer affected by large differences in porosity and pebble inclusions (Gaffney and Gater 2003). Some laboratory instruments are also able to measure differences in frequency responses that can be diagnostic of the types of magnetic minerals present in the sample (Clark 1996), which in turn can indicate the age and possible prehistoric use of the soil (Dalan 2006).

Another configuration that is just beginning to receive attention among archaeologists is down-hole MS. Single- or dual- coil instruments are lowered down a core hole to measure MS at increasing depths. This method represents a very different approach to archaeological geophysics that will no doubt receive more emphasis in the coming years. Dalan (2001, 2006) has pioneered the use of down-hole MS in archaeology, and has shown that these data can help locate buried soil horizons, cultural strata, and features, and answer questions about cultural formation and post-depositional processes. Of particular interest is the fact that surface MS data are very limited in depth penetration, but down-hole data offer much greater exploration depths.

Depth and Resolution. Of all the geophysical methods described here, MS collected across the ground surface is the most limited in terms of depth sensitivity owing to the weakness of magnetic fields measured. Exponential loss occurs as the electromagnetic field enters the ground, and then again as it travels from the ground to the measurement sensor. The loss is exponential to the sixth power, resulting in very poor depth penetration (Clark 1996).

There are substantial differences between the depth sensitivities of single- and dual-coil instruments. Single coil instruments must be in direct contact with the ground, and the depth of penetration is limited by the diameter of the search loop (Dalan 2006). The Bartington MS2D single-loop sensor, for example, penetrates only to about .10 m below surface. Dual coil sensors, such as the Geonics EM38 have a penetration on the order of a half a meter or more (depth sensitivity is greater, however, for conductivity with this sensor). For anything deeper than about .70 m, the only option is a down-hole sensor or recovery of samples from soil cores for lab analysis.

Data densities for MS area surveys depend on the instrument. Dual-coil sensors are fast and typical data densities are much the same as for conductivity, perhaps .25 x .5 m (i.e., 4 readings per linear m, with traverses spaced at .5 m intervals). Single coil sensors, however, are considerably slower because each reading requires direct contact with the ground and often the sensor must be zeroed before each measurement. Sampling densities are therefore typically on the order of one (or less) measurement per square meter. This puts an obvious limit on spatial resolution. With dual-coil instruments spatial resolution is similar to conductivity. Spatial resolution of down-hole sensors varies. Until the recently developed Bartington MS2K, the resolution of most downhole sensors was not sufficient to resolve thin layers (Dalan 2006).

Advantages and Disadvantages. Magnetic susceptibility surveys are hugely underutilized in archaeology both in Europe/UK and the United States. One reason might be the complexity of the instrumentation, and the limits to depth penetration. Another disadvantage is the current lack of stable and streamlined instruments. The EM38 is widely available, but it is prone to drift and the data are sometimes difficult and time consuming to process. There are many advantages to MS, however, and they are just now being realized. The fact that MS measured with EMI is an active method means that it is not limited to the direction and strength of the earth's magnetic field (as opposed to fluxgate magnetometry), so it can resolve features regardless of geometry. The most obvious outcome of this is the fact that MS data are absolute values, rather than a collection of positive and negative poles (as with magnetometry). Some surveys have demonstrated that MS can detect subsurface cultural features that are not detected with magnetometry (Kvamme, et al. 2006) (Figure 7). The Geonics EM38 is probably the best for rapid area coverage and good depth penetration for typical archaeological applications.

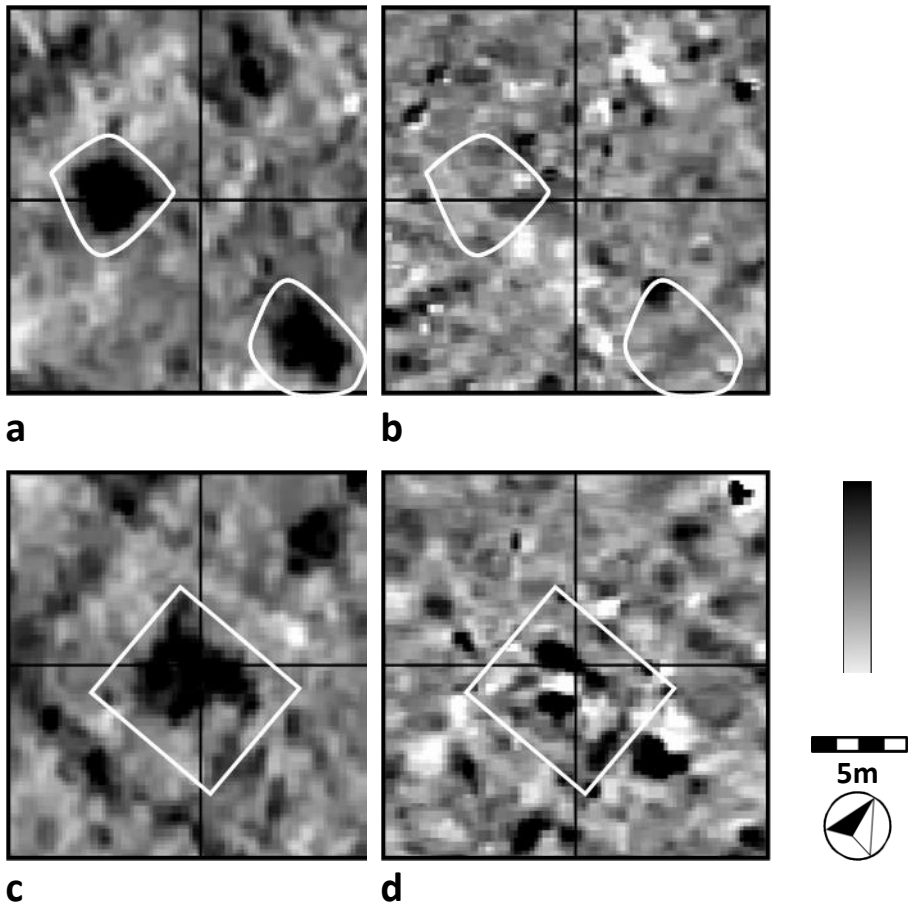


Figure 7. Comparison of magnetic susceptibility (MS) and magnetometry data from an early pueblo site in the American Southwest: (a) MS data showing two pithouses; (b) the same two pithouses are not visible in the magnetometry data covering the same area; (c) MS data showing a pit-structure; (d) magnetometry data over the same area, showing anomalies that probably represent the edges of the pithouse floor and a perhaps a central feature. MS data were collected with a Geonics EM38, and magnetometry data with a Geoscan FM36.

2.2.4 Magnetometry

Property Measured. Magnetometry is a method of passively measuring magnetic fields. For archaeological applications magnetic fields are usually measured in nanotesla (nT). A nanotesla is 10^{-9} Tesla, the standard SI unit of measure for magnetic fields. Two types of magnetism are measured simultaneously with magnetometry: induced and thermoremanent. Induced magnetism is directly related to MS, but a magnetometer measures it in a different way than EMI. The difference lies in the source of the inducing magnetic field. EMI sensors create an electromagnetic field directly above the ground and measure the response from nearby materials. The passive magnetometer, on the other hand, relies on Earth's magnetic field as the primary inducing field and can only measure its localized effect without control over its direction (Witten 2006). Since the

Earth's magnetic field is omnipresent, magnetic fields directly below the instrument can be strengthened or reduced by neighboring fields (Clark 1996). Two very similar features next to each other can therefore cancel each other out in magnetometry data because of their overlapping magnetic fields (Aitken 1974; Clark 1996); though in the majority of cases adjacent anomalies only weaken the overall magnetic fields measured, rather than completely cancel one another.

Magnetometers also measure thermoremanence, which is a permanent magnetic field that is created when a material is heated, and is independent of an external magnetizing field (Clark 1996). Heating is a major factor for magnetic methods because it not only enhances MS but also causes thermoremanence. Even small amounts of heating produce some thermoremanence (Tite 1972), but if materials are heated beyond the Curie point (around 600 C, depending on the material) (Clark 1996; Reynolds 1997) their magnetic particles align with the earth's magnetic field and are "frozen" in that position upon cooling. This makes them strongly magnetic, because of the net effect of all the magnetic domains added together (Kvamme 2006b). This process happens naturally when volcanic lava or magma within the earth cools to form igneous rocks (Reynolds 1997), and also from human use of heat and fire (Clark 1996). Magnetometry surveys can detect many of the modifications that humans make to the Earth's surface (Kvamme 2006b). Fire pits, burned agricultural fields, and burned houses are readily detected because of their enhanced MS and thermoremanence. The firing of clay to make bricks and pottery also has a thermoremanent effect, making them potentially detectable depending on their size and depth. Pottery sherds are generally not identified by magnetometry, but large intact ceramic vessels have been detected (Kvamme 2006b). The fact that topsoil is magnetically rich compared to subsoil, and is further enhanced by human actions makes possible the detection of various cultural features that involve the accumulation or removal of topsoil. Earthen house walls and roofs are sometimes made of topsoil, as are various types of mounds. Removal of topsoil to create ditches, recesses in house floors, and pits can create magnetic voids that may have been partially or completely filled with topsoil after abandonment (Clark 1996; Kvamme 2006b). Constructions that utilize stone, such as house foundations or pavements are also often detected with magnetometry survey because the stone's magnetic properties contrast sufficiently with surrounding materials. Finally, iron artifacts are highly magnetic and can be readily detected. In some cases modern metal debris is a major source of clutter in magnetometry surveys, but in other cases, particularly North American historic sites, the systematic detection of iron artifacts is a great advantage (Bevan 1998; Kvamme 2006b).

Method of Measurement: Three basic types of magnetometers are commonly used in archaeology: proton precession, optically pumped, and fluxgate. Proton precession magnetometers were the first to make magnetic survey practical for archaeology (Clark 1996). Their operation relies upon the effects of local variations in Earth's magnetic field upon the spin of protons (the nuclei of hydrogen atoms) (Clark 1996; Witten 2006). First, the protons in a bottle of hydrogen-rich fluid such as water or alcohol are polarized (made to align) by passing a current through a coil of wire that surrounds the bottle.

Next the current is turned off, allowing the protons to spin ("precess") and realign with the local magnetic field. The precession of the protons generates a slight alternating current, which is measured by the coil, and whose frequency is proportional to the strength of the ambient magnetic field (Clark 1996; Witten 2006). In essence, a strong ambient magnetic field will cause rapid spinning (precession), creating a high frequency, whereas a weaker magnetic field causes slower precession, and therefore a lower-frequency. Each measurement with proton precession takes almost one second (Witten 2006) making this the slowest type of magnetometer. For this reason it is not often used for survey today, but is still used for teaching and as an affordable alternative to other magnetometers (Kvamme 2006b).

Optically pumped magnetometers (also known as optical absorption magnetometers and including cesium vapor, alkali vapor, and rubidium magnetometers) are similar to proton precession magnetometers in that they utilize the precession of atoms when exposed to a magnetic field (Clark 1996). Instead of using an induced current in a coil to polarize atoms, they measure the changes in optical transparency of alkali vapors (usually cesium, but also rubidium) when exposed to a magnetic field. When polarized light is passed through the vapor, the intensity of the transmitted light is proportional to the ambient magnetic field (Clark 1996; Scollar, et al. 1990; Witten 2006). Cesium vapor magnetometers (Figure 7a) are probably the most commonly used of the optically pumped magnetometers in archaeology.

Fluxgate magnetometers use a metal rod around which a coil of copper wire is wound (Clark 1996). An external magnetic field, such as the Earth's magnetic field or nearby remanent fields, magnetizes the metal rod, which in turn causes a current to flow through the copper wire (Witten 2006). The current is measured and is proportional to the strength of the component of the external magnetic field that is *parallel* to the axis of the rod. This means that fluxgate sensors are direction sensitive, and much more so than precession magnetometers. They are usually configured to measure the vertical component of the magnetic field. They are also extremely sensitive to very minor variations in sensor tilt, so that they are not practical unless used in a gradiometer configuration (see below). Though rarely used for non-archaeological applications, fluxgate gradiometers are standard in archaeological geophysics and most are designed explicitly for archaeology (Figure 8b-c).

Configurations. Magnetic surveys of archaeological sites can be conducted in one of two ways. The earth's total magnetic field can be measured using a single moving sensor, or the magnetic field gradient can be measured by moving a pair of sensors (Bevan 1998; Clark 1996; Gaffney and Gater 2003; Heimmer and De Vore 1995; Kvamme 2001, 2006b; Scollar, et al. 1990). In fact, both approaches require the use of two sensors. If a single sensor is systematically moved across the survey area, a second sensor must be kept in a stationary position to record diurnal variation in the earth's magnetic field. Diurnal variation — which is generally far more substantial than that associated with archaeological deposits — is removed by subtracting it from the roving magnetometer measurements (Clark 1996; Kvamme 2001). This difference represents the spatial component of the variation in the magnetic values.

When a pair of sensors is moved together across a site, the magnetic field gradient is directly measured (Clark 1996). Gradiometers consist of a pair of proton precession magnetometers, cesium vapor (Figure 8a) or other optically pumped sensors, or fluxgate sensors (Figure 8b-c). Figure 9 illustrates how a gradiometer works. First consider the two sensors (top and bottom) separately and how they would detect a feature buried less than 1 m deep. The distance between the bottom sensor and the buried feature is 1 m, and the top sensor is .5 m higher. Also assume that the ambient magnetic field is about 52,000 nT. In the example the magnetic field strength in the vicinity of the lower sensor is 52,001 nT, which is the ambient magnetic field, plus the localized magnetic anomaly created by the buried pit feature. The top sensor also detects the pit, but the localized magnetic field strength would only be 52,000.3 nT, because of the fall-off in magnetic field strength with the third power of distance ($1/(1.5^3)$). This measurement therefore characterizes the background (ambient) magnetic field, even though it is slightly influenced by the pit feature. When the top sensor reading is subtracted from the bottom sensor reading, the resulting gradient records the pit feature anomaly as 0.7 nT (52,001 – 52,000.3 = 0.7 nT). This is important because throughout the day the ambient magnetic field strength will change drastically, but the gradient due to subsurface features will be the same.

a **b** **c**

Figure 8. Commonly used magnetometers: (a) Geometrics G-858 Cesium gradiometer re-configured for archaeological use; (b) Geoscan FM-256 fluxgate gradiometer; (c) Bartington Grad601-2 dual fluxgate gradiometer system.

The example given in Figure 9 also illustrates the reduced sensitivity of the gradiometer compared to a total field configuration. Using a total field configuration (second sensor placed at a permanent base station), the pit feature would be recorded as 1 nT (52,001 – 52,000 nT), compared to .7 nT recorded by the gradiometer. In fact, as the top sensor is moved farther away from the bottom sensor, the sensitivity of the instrument to subsurface features is improved. For example, if the top sensor were positioned .5 m higher, the magnetic gradient would be .875 nT ($1-1/(2^3)$), a twenty percent increase compared to the .5 m sensor separation. In summary, the feature in the example would be recorded as 1 nT with a total field configuration, .875 nT with a

one-meter sensor separation gradiometer, and .7 nT with a .5-meter sensor separation gradiometer. Since there are other problems associated with using a total field configuration (mainly mismatches in the timing of measurements and added data processing time), often a gradiometer is preferred. A gradiometer with sensors separated by 1 m has greater sensitivity than one with .5 m separation, but the smaller sensor separation has the advantage of less error due to sensor tilt, with only a modest sacrifice in sensitivity. A variety of gradiometer and total field configurations are used in archaeology with great success.

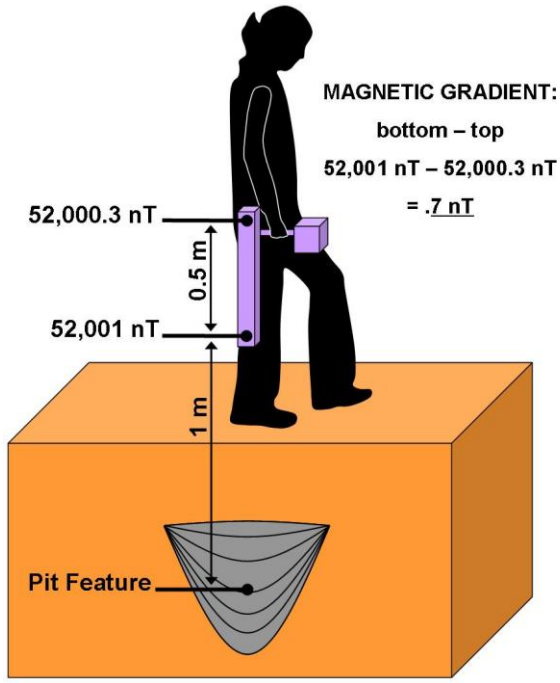


Figure 9. How magnetic gradiometry works and why it is less sensitive than total field configurations. In this example the ambient magnetic field is 52,000 nT. The pit feature creates a local increase in the magnetic field of 1 nT at a height of 1 m, where the bottom sensor is located. The top sensor also records the pit feature anomaly, but only at 0.3 nT because of the greater height. The pit feature is therefore recorded as 0.7 nT (gradient).

Depth and Resolution. The ability to detect an object depends on its magnetic properties and distance from the sensor. In most cases anomalies detected with a magnetometer of any type lie in the uppermost 1-2 meters, with a maximum of about 3 meters (Clark 1996). There are exceptions to this of course, as large iron masses or heavily burned features can be detected at much greater depths. The general rule is that the strength of a magnetic field falls off inversely as the third power of its distance (depth plus sensor height) from the sensor (Clark 1996). This means that if a feature's magnetic field is measured as 1 nT at one meter in the ground, the same feature would measure only .125 nT at 2 m deep. This is at the limit of detection for most magnetometers, making the feature barely detectable at 2 m. Since many

archaeological features at North American prehistoric sites are only weakly magnetic, they are virtually undetectable when buried more than 2-3 meters.

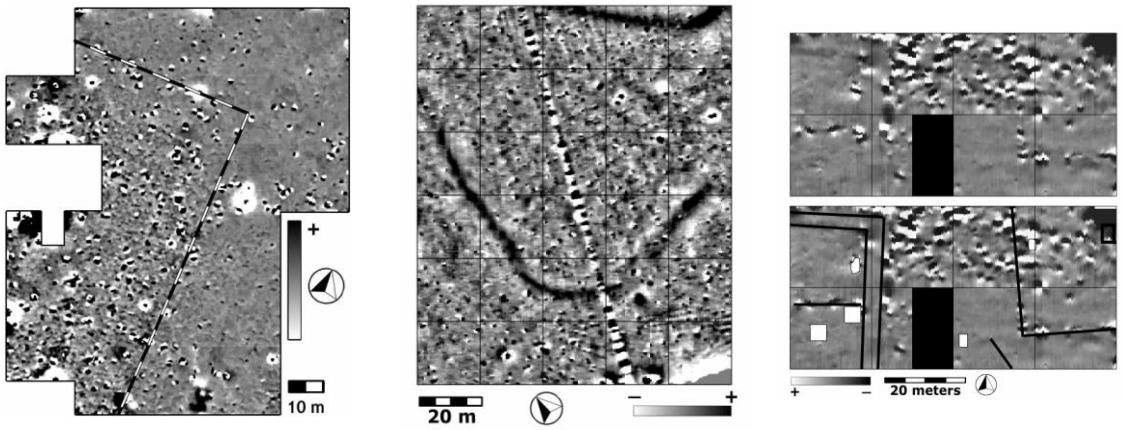
There are a number of "rules of thumb" for estimating the depth of features based on their magnetic anomalies. The half-width rule states that the width of an anomaly at half its maximum value equals either the depth of the feature (Kvamme 2006b), or its width if that number is greater (Clark 1996). The half-maximum value is most easily located when data are displayed with isolines (contours). Find the maximum value of the anomaly, divide that in half, and locate that value along the slope away from the anomaly peak. The distance between this and the anomaly peak equals the approximate depth of the feature below the sensor. Witten (2006) adds another factor to this rule – multiply the half-maximum value by 1.3 to take into account the decay of magnetic field strength with the cube of distance. To the contrary, Bevan (Bevan 1998) suggests that the half-width rule (without multiplying by 1.3) often overestimates depth because it assumes a spherical mass of iron, which bares little resemblance to typical archaeological targets. Note that in all cases "depth" is actually the distance between the anomaly source and the magnetometer, so the height of the instrument should be subtracted to calculate depth below the ground surface (Bevan 1998; Kvamme 2006b; Witten 2006).

Another useful, more general rule of thumb allows the relative depths of features to be estimated. Witten (Witten 2006) states that as a feature's depth increases, the change in magnetic measurements from the maximum value outward is more gradual. In other words, anomalies from deeper targets have lesser slopes. In a contour plot the deeper anomalies will have more widely spaced isolines. The shallower the feature, the more closely spaced will be the contour lines.

Magnetometry is probably the fastest geophysical method used in archaeology, especially if dual sensors are used. Fluxgate and cesium sensors can take measurements very quickly, allowing sampling intervals of eight to sixteen measurements per meter along transects while the surveyor walks at a brisk pace. Even at double the speed of single-sensor surveys, the number of transects per meter is often no greater than two. This is because many prehistoric and historic features are large enough to be detected by half meter transects, and the benefit of surveying nearly twice as much area is often greater than covering a small area with a higher sampling density. In some cases areas of special interest are selected for re-survey using higher sampling densities, based on the results of a more coarsely sampled initial survey.

Advantages and Disadvantages. Magnetometry has long been used in archaeology with great success. As noted above, a great variety of human behaviors leave magnetic features on the landscape. There are problems with the method, however, and many of them have to do with interference from modern metal debris. Even very small pieces of ferrous metal, such as old bottle caps, artillery shells, and fragments of metal pin-flags cause very large anomalies in magnetometry data that sometimes obscure other, more subtle ones. One common example is that archaeologists leave metal pin-flags that fall over, become trampled by livestock, or are run over and chopped up by mowers. Each piece of pin-flag left on the ground can create a large dipolar anomaly that prevents

detection of nearby features of lesser contrast (Figure 10a). In addition, buried utilities are common in many parts of the world, and can make large areas unsuitable for magnetic survey (Figure 10b). A similar type of interference can also come from nature in the form of igneous rocks. If the local bedrock is igneous or contains veins of iron-rich minerals, and is close to the surface, the interference can preclude magnetic survey (Clark 1996). In some cases, however, igneous rocks are imported for building stone or some other cultural purpose, and their locations can be readily detected (Figure 10c). A final factor to consider is the level of soil development. Soil is more magnetic than sediment, and is the reason that many features such as pits, earthen constructions, and ditches can be detected. In areas with little or no soil development, such as deserts, magnetic anomalies can be extremely subtle and may not have enough contrast to be detected (Kvamme 2006b). Despite these disadvantages, magnetometry is often considered the workhorse of archaeological geophysics because it can cover large areas rapidly, and is particularly sensitive to archaeology (Kvamme 2006b).



a **b** **c**

Figure 10. Examples of clutter in magnetometry data: (a) pin-flags litter the surface of this late prehistoric site, and are particularly dense inside the excavation grid boundary (south and west of dashed line), where most research efforts have been focused. The location of several steel datums (rebar) are also visible as very large negative anomalies; (b) a metal culvert bisects this site in Georgia; (c) top image: imported andesite cobbles are scattered about the surface in this area of Tiwanaku (Bolivia), adding clutter to the data, but careful examination (bottom image) shows the boundary of a sunken temple (left) with a magnetic interior wall, and a later structure wall (right).

2.2.5 Ground Penetrating Radar (GPR)

GPR instruments work by transmitting electromagnetic energy (very high frequency [VHF] radio pulses) into the ground and measuring the amount of energy that is reflected back and the time it takes to reach the surface (Bevan 1998; Conyers and Goodman 1997; Gaffney and Gater 2003; Kvamme 2001). Soils, rocks, buried objects and features differ in the degree to which they absorb or reflect the energy. Radar pulses are reflected back to the surface more quickly from shallow objects than from those that are deeper. The time required for reflectance can be used to estimate the depths of objects and surfaces, so this technique has great benefits for archaeology.

Property Measured. GPR is, in a sense, a method for measuring dielectric permittivity, a property that influences a material's ability to transmit an electrical current. Archaeologists don't focus so much on this property, however, (which is a little less familiar than resistance, conductance, and magnetism) as they do on the means of measuring it, and implications of variation in the resultant data. GPR sensors measure the travel time in nanoseconds (ns) (one ns is one billionth of a second) and intensity of electromagnetic (radar) energy that is reflected off subsurface materials and objects in decibels (dB) (Burger, et al. 2006; Witten 2006). Wave velocity is inversely proportional to relative dielectric permittivity (RDP). By far the greatest factor affecting RDP is moisture (Conyers 2004), which is positively correlated with RDP. Energy reflection can also be affected by magnetic permeability, but only in rare cases such as when iron or iron oxides are present in very high concentrations (van Dam and Schlager 2000).

Reflections are created in the ground at interfaces between materials where there is a change in relative dielectric permittivity, and thus, in wave velocity. Radar waves traveling through dry sand, for example, will slow down when they encounter a layer of wet sand. At that interface, some of the energy is reflected, while the rest is transmitted further into the ground where it can be reflected at deeper interfaces (Conyers 2004). Some of the transmitted waves are also refracted, or bent as they pass through the interface much like light bends as it enters water. The strength of reflections, as well as the angle of refractions can be calculated using simple equations (see Conyers 2004; Witten 2006). Reflection strength is governed by the contrast in materials above and below the interface. Stronger reflections are generated from interfaces where there is a greater difference in dielectric permittivity between the two layers. This means that if the change is very subtle, reflections will be weak and barely detectable. With high contrast, reflections are very robust. The ideal situation is therefore moderate contrast, because reflections will be strong enough to detect material interfaces, but not so strong that they reflect most of the energy and block transmission to greater depths. Most archaeological materials are of low to moderate contrast, and there is rarely any problem of too much contrast. Problems arise, however, with the presence of large pieces of metal (metal reflects 100% of the signal), and with water saturation or if the water table intersects with archaeological layers. Metal is not a problem, of course, if it is the target of interest such as detecting graves with metal coffins.

Reflections are simple enough to visualize when they are considered individually, but the combination of reflection and refraction of waves through multiple interfaces of varying shape and orientation is much more difficult to imagine. Waves can pass through one interface such as the top of a clay layer, then reflect off the bottom of that clay layer, and then repeatedly reflect up and down between the top and bottom of the layer. If some of these signals eventually reach the receiving antenna, each reflection is recorded, making it appear that there are multiple interfaces. These are called multiples (Conyers 2004). Another important issue is that many reflected waves are angled away from the receiving antenna. Some reflected waves never reach the antenna, so only a fraction of reflections are actually recorded (Figure 11a). Yet another issue is that radar energy transmission actually emanates outward from the antenna in all directions (Conyers 2004). Many antennas are shielded, so that energy is not radiated above ground, but the transmission into the ground remains a cone (with the antenna at the apex) rather than a straight line (Conyers 2004) (Figure 11a). As the antenna is moved along the ground surface energy radiates not only downward, but outward ahead of the front of the antenna, behind it, and to both sides. This is how hyperbolic reflections originate from a point source or small spherical object (Conyers 2004; Witten 2006). Reflections continuously occur as the antenna approaches the object, passes directly over it, and then continues farther along the line (Figure 11b). Since the GPR system does not "know" the direction that the receiving waves come from, it assumes all reflections are from straight down in the ground (Figure 11c). So the "tails" of the hyperbola represent the edges of the object as they were detected from the antenna on either side of it, and the peak represents its actual location and depth recorded when the antenna was directly above (Figure 11c-d).

Method of Measurement. Reflection strength is measured by the amplitude of reflected waves (in dB), and the time it takes for radar waves to travel from the transmitter, be reflected, and then reach the receiver is recorded in ns. Reflections are recorded continuously, such that for every horizontal location on the ground there are hundreds or even thousands of measurements called samples. The relationship between nanoseconds, samples, and traces is illustrated in Figure 12a. Each trace is composed of hundreds of samples, but the vertical axis is usually expressed in nanoseconds or depth if velocity is known. Depth is calculated using the basic relationship: velocity equals distance (depth) divided by time ($v = s/t$) (Conyers 2004). The easiest way to approximate depth is to estimate velocity based on the ground conditions (moisture and sediment type). It is more accurate, however, if actual depths are known for a few reflections. Knowing depth and time, the average velocity is determined, and this figure used to convert all data to depth assuming there is little variation in the survey area. More details on depth calculations are included below.

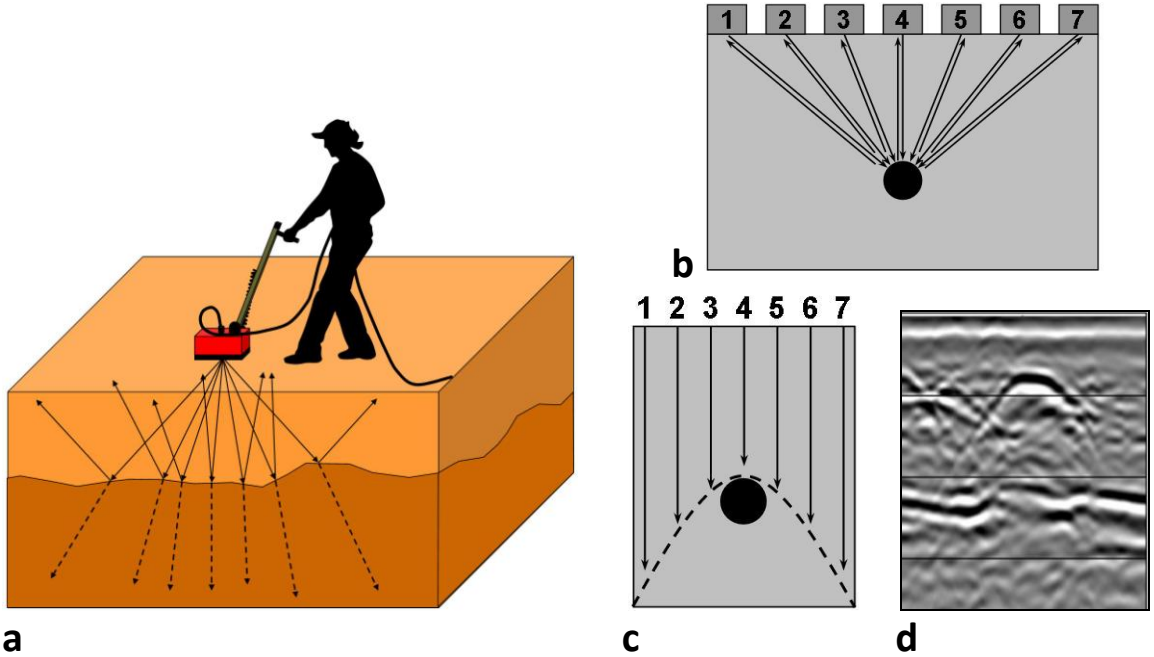


Figure 11. Ground Penetrating Radar ray path geometry: (a) When a shielded antenna is used, radar pulses are radiated downward in a cone shape, and are reflected (solid lines) and refracted (dashed lines) at material interfaces. Reflection hyperbolas and other complex reflections are created because of this cone-shaped pattern. (b) As the antenna passes over a point source object from position 1 to 7, the length of time taken for each pulse to be reflected back is recorded, and then (c) plotted as if it were directly beneath the antenna. (d) Reflection hyperbola generated from a segment of steel rebar inserted into a trench wall.

Most geophysical data are displayed by plotting the values in a map and creating isoline (contour) or continuous shade (image) maps by gridding and interpolation. This is a logical way to display most geophysical information when there is one measurement per unit area. With GPR, however, there are thousands of measurements per linear meter. The original way of displaying the information was by radargrams, also known as reflection profiles (Figure 12a). These are two-dimensional (profile) maps showing GPR reflections, and are loosely analogous to a map of the wall of a backhoe trench. A series of closely spaced reflection profiles are typically acquired for archaeological applications (Figure 12b), which makes it possible to interpolate the data into a three dimensional cube (Figure 12c) or horizontal slice maps (Figure 12d). For many years only reflection profiles were used for interpretation, and plan-view maps were made by interpreting each profile, making notes of the location and depth, and plotting these on a map (Conyers and Goodman 1997). Eventually the process of mapping reflection amplitudes in plan-view maps representing specific time (or depth) intervals was automated by computer (Goodman, et al. 1995), and now slice maps (Figure 12d) are routinely used. Slice maps are a vast improvement for archaeological GPR and have made it easier for non-specialists to interpret and understand the data. There are still many cases where it

is necessary to use the original profiles for better interpretations (because reflections are often not shaped like the object that created them), but slice maps make it easier even for specialists to understand what their data show.

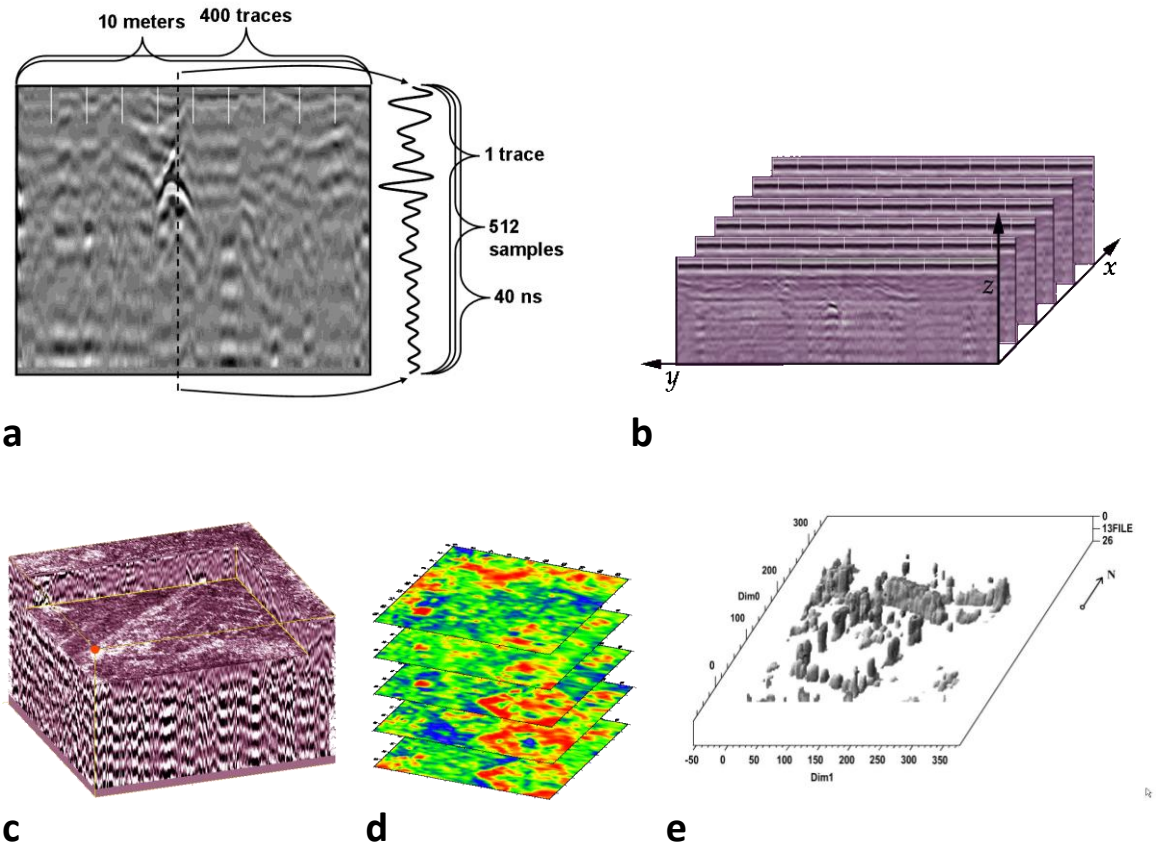


Figure 12. Display of Ground Penetrating Radar data. (a) Reflection profiles show data collected along one transect across the ground surface, and the view is roughly analogous to the wall of a backhoe trench. (b) Each (x,y) location on the ground surface is represented by one trace of data in the (z) direction, which is measured in both nanoseconds and samples. A series of closely spaced reflection profiles are typically collected for archaeological mapping. This makes it possible to (c) interpolate the data into a three-dimensional cube, (d) generate time or depth slices representing plan-view maps at discrete intervals in the ground, and (e) create 3D isosurfaces (after Conyers, et al. 2002).

Configurations. Ground Penetrating Radar instruments can be configured in a number of ways, depending on the type and frequency of antenna used, the size and weight of the instrument, and whether or not a survey wheel is used. Older GPR systems are almost always configured so that the main computer and power source (often a 12-volt battery) are left in one place (Figure 13a). A long cable is used to connect to the antenna, which is moved back and forth across the survey area (Figure 13b). As technology continues to improve, more and more systems are built light enough to be moved along with the antenna, often harnessed to the person pulling the antenna or

wheeled along in a cart. During a survey at Tiwanaku (Bolivia) with a GSSI sir-2000, only a very short cable was available so the main computer and battery were placed in a wheel-barrel and wheeled alongside the antenna (Figure 13c). Some of the newest GPR systems, such as the GSSI SIR-3000, are small enough to be carried by a harness attached to the same person pulling the antenna, and can also be mounted on a push-cart. Antennas also vary quite a bit. A GPR "antenna" is actually two antennas, one transmitter and one receiver. Sometimes the two are spaced as closely together as possible (called "coincident") and housed in one box so you cannot see them or separate them (e.g. GSSI antennas). Others are made so that the transmitter and receiver are separate and can be moved farther apart if a greater separation is desired (e.g. Sensors & Software antennas). In most cases a survey wheel can be attached (Figure 13b), which keeps track of the distance traversed and controls the rate of recording. For archaeology, coincident transmitter-receiver configurations, or very small separations are typically used. Survey wheels are also preferred when they are available, especially if there are obstacles to continuous movement of the antenna. Without a survey wheel, the antenna must be moved at a fairly constant pace, and fiducial markers made at close intervals (1 m is common) to keep track of distance.

a **b** **c**

Figure 13. Configurations of the GSSI SIR-2000 GPR system: (a) Control unit with keyboard attachment and 12-volt battery power; (b) 400 MHz antenna with survey wheel; (c) "the wheel-barrel method" (not recommended).

Depth and Resolution. The depth and resolution capabilities of GPR depend on several factors and require a fairly detailed explanation. Speed and sampling densities depend on instrument settings and survey method, and both depth sensitivity and spatial resolution depend on ground conditions (moisture, sediment type) and antenna frequency.

Ground Penetrating Radar survey has a reputation for being relatively slow compared to other methods, but newer systems allow for much faster data collection that is on par with resistivity, and even EMI surveys. Slow surveys are typical with older systems where the computer must remain stationary while the antenna is moved back

and forth and tethered by a cable. This can be especially time consuming where there are abundant obstacles that snag the cable, and often requires two or three people to keep the survey going uninterrupted. Newer systems that allow the entire instrument to move as one allow for more rapid survey, and only one person is needed to operate the instrument.

The sampling density of GPR data is similar to other geophysical methods in the x direction, but much higher in the y (along transects) and z (vertical, or depth) directions. The x direction is simply dictated by spacing between transects, where .5 m is common, but in some cases 1 m is adequate and .25 m is sometimes used for detailed surveys. The sampling density along traverses (y) is variable, and can be controlled by a survey wheel or by the speed at which the antenna is pulled. When using a survey wheel, the number of traces (measurements, also known as wiggles or scans) per meter can be set in the computer and will be constant as long as the antenna is not moved excessively fast. In the vertical (z) dimension the number of measurements is dictated by the size of the time window (in nanoseconds) and the number of samples per trace. The time window is the length of time the computer will "listen" for radar reflections (recorded in two-way travel time, or the length of time it takes for the radar pulse to travel from the transmitter, be reflected, and then recorded by the receiver). Each trace is made up of a series of measurements, called samples (Figure 12a). The more samples per trace, the more detail will be recorded in the shape of the trace (recorded signal). A typical GPR survey in a 50 x 50 meter area might entail profiles (transects) spaced .5 m apart, with 50 traces per meter, a time window of 50 ns (two-way travel time, TWTT), and 500 samples per trace. Without knowing velocity, depth is not known so the third dimension of the voxels (three-dimensional pixels) cannot be determined in meters. The resulting cube of data, however, would have the dimensions x = 100 (profiles), y = 2,500 (traces), and z = 500 (samples). If velocity was calculated to be .10 m/ns (TWTT), then the depth would be 2.5 m (50 ns x [(.1m/ns)/2]). The sampling densities would therefore be .5 m in x, .02 m in y, and .005 m in z. In other words there is a profile every .5 m, a trace ever .02 m, and a measurement sample for every .005 m in the ground (down to 2.5 m).

High sampling densities are necessary for interpreting reflection profiles, but they can be greatly reduced for time slices. Using the same hypothetical survey, the data might be divided into twenty equal depth slices each representing .125 m of earth. For displaying these as two-dimensional images it is wise to resample so that there is a more equal sampling density in x and y, such as .25 x .25, or .5 x .25. Another way to visualize GPR data is by 3D rendering. By interpolating between reflection profiles, a continuous 3D data set is rendered (Figure 12e) with transparent background values so that high amplitude reflections are visualized within a 3D volume. This is a great tool for interpretations and exploring data, but usually does not translate well onto paper so slices and reflection profiles are still the most common method of displaying GPR data in print.

Depth sensitivity in GPR is directly related to the conductivity of the ground. Most ground is at least slightly conductive, so some of the energy is attenuated, or converted to electrical currents and dispersed, before it ever reaches the receiving antenna (Conyers 2004). As radar waves move more deeply into the ground, less and less energy

is available for reflection so there is a loss of the signal with depth. Often GPR practitioners will describe highly conductive soil conditions as “lossy”, which means that very little of the signal ever makes its way to the receiving antenna because most of it is attenuated. To counteract this decay the GPR signal is “gained,” or multiplied by increasing values with depth (Conyers 2004). The most important factor dictating the degree of attenuation is moisture. Attenuation is exacerbated by the presence of electrolytes, and clay minerals, which often retain moisture even in very dry climates. It is frequently said that the success of a GPR survey is dictated by the amount of clay present in the ground, but this is not always the case. Conyers (2006a) has shown that the most important factor is moisture, and even the most conductive clay minerals are not very conductive when dry. There is also great variation in the types of clays, and in one instance Conyers (2006a) conducted a very successful GPR survey in wet clay in western Oregon. Subsequent soil tests revealed that the grains were actually clay-sized, but were not clay minerals. Even though it looked and felt like clay, it was not mineralogical clay and therefore not detrimental to the GPR survey (Conyers 2006a). Conversely, one can be fooled by dry desert settings, assuming GPR transmission will be ideal, but the presence of salt coupled with only a small amount of moisture can create high conductivity and therefore excessive attenuation.

The other factor affecting depth, and unfortunately spatial resolution, is frequency. A very low frequency antenna, such as 50 MHz, might penetrate to 50 meters or more, but this would result in very coarse spatial resolution (Conyers 2004). Conversely, a high frequency antenna, such as 900 MHz, might only penetrate to one meter or less, but is capable of resolving very small features on the order of tens of centimeters. There is a consequent tradeoff between depth sensitivity and resolution. Lower frequencies might allow deeper penetration, but only at the loss of spatial resolution. A “rule of thumb” is that a feature must be at least 25 percent of the *downloaded* wavelength that reaches them to be detected (Conyers 2006a). *Downloading* of radar energy always occurs as energy passes in the ground and decreases in frequency. A 400 MHz center frequency antenna, for example, will have a downloaded frequency of about 300 MHz depending on the RDP of the ground. The wavelength would change from about .75 m in air to about 1 m in the ground. In such a case you could say the spatial resolution is about .25 m. Fortunately GPR antennas are broad band, which means they actually produce a wide range of frequencies on the order of one-half to two times the center frequency (Conyers 2004). A 400 MHz center-frequency antenna, for example, actually transmits frequencies ranging from roughly 25 to 1000. This means that the downloaded frequencies, while lower, still contain some high frequencies for resolving smaller features as well as lower frequencies that might penetrate to deeper in the ground. Portions of the frequency spectrum can be enhanced or subdued with frequency filters during data collection or later while processing if desired.

For most archaeological sites, there is a narrow range of suitable (center) frequencies. A frequency of about 200 MHz might be used in archaeology, but only to find relatively large features that are too deeply buried to be detected by a higher frequency antenna (e.g. Casana, et al. 2008). At the other extreme, a 900 MHz antenna might be used to detect very small features buried close to the surface. In many cases,

however, very high frequencies are too sensitive to small objects (particularly rocks) and data are therefore very cluttered and difficult to interpret. The vast majority of successful GPR surveys in archaeology are conducted with antennas in the range of 400-500 MHz, with depth sensitivities ranging from .5 to 3 and sometimes 5 meters in very favorable ground conditions. It is important to note that even though lower frequency antennas will generally penetrate deeper into the ground, the ultimate control on depth is ground conditions. If there is a layer of highly conductive material, such as saltwater, depth penetration will be truncated no matter how low the frequency (Conyers 2004).

Depth of penetration can be calculated in a variety of ways. If time allows and there is an exposure such as a backhoe trench available, the easiest way to determine depth is to do a "bar test" (Conyers and Goodman 1997). This test involves inserting a metal bar (such as a small pipe or rebar section) into the trench wall and collecting a reflection profile above it along the edge of the unit (Figure 14a). Since you can measure the actual depth (s) to the bar with a tape measure, and you can determine the travel time (t) by finding the reflection in the profile and dividing it in half (original time is recorded as two-way) (Figure 14b), then you can determine the average velocity (v) of radar wave propagation between the ground surface and the bar using the relation:

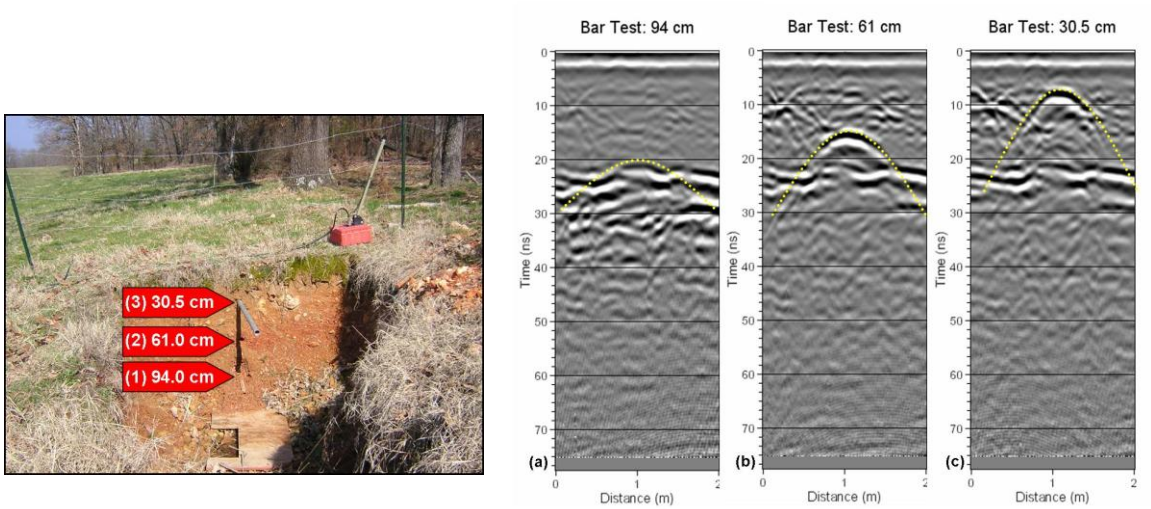
$$v = s/t$$

Once the velocity is known, the same equation is used to convert all times to depth by rearranging the equation as:

$$s = vt$$

Applying this conversion to all profiles would transform the entire data set from time to depth. This is often useful, but it is also important to note that velocity can vary a great deal both vertically and horizontally as moisture and lithology change spatially. One velocity calculation may not accurately represent the entire data set. It is better to do this test at multiple depths in the same trench, and at several trenches located throughout the survey area. Unfortunately, not all software programs allow the conversion of time to depth at multiple locations, so often one constant is used that is thought to best represent the average velocity of the general survey area. When doing this, choose a velocity calculation from a depth that is as close as possible to the average depth of cultural deposits so that depth calculations for cultural features may be more accurate than for objects located above or below them.

A very similar velocity test can be done if the depth to any recognizable discrete source of reflections is known (Conyers 2004). If there is a water pipe or other utility that cuts through the site and the depth is known, it should be recognizable by hyperbolic reflections in profiles. The information can therefore be used in exactly the same way as a bar test. Other reflections, such as stratigraphic layers, can also be used, as long as they can be recognized in reflection profiles and their depth is known.



a **b**

Figure 14. Ground-Penetrating Radar Velocity Bar Test: (a) a metal bar was inserted into a trench wall at three different depths; (b) reflection hyperbolas from each depth. In this case the test was done at 94, 61, and .305 m. (The reflection from the deepest bar persist in each test because we were unable to retrieve the bar after the initial test.)

Another velocity test that can be done in the field is called a common midpoint (CMP) test. This requires that the transmitter and receiver be separated at increasing distances from each other. Only some GPR systems have antennas that can be separated like this, but the test can also be done with two complete antennas of the same or similar frequencies as long as you have a cable splitter or the computer has two channels to receive data simultaneously. In any case, as the transmitter and receiver are moved farther apart, waves that travel through the air, directly through the ground, and through deeper and deeper layers are recorded. As the test proceeds, energy continues to travel through different layers, and if the arrivals of these waves can be identified in the data, and the distance is known (measured along the ground), velocity can be calculated using the same relation as above (for the reflection test) (Conyers 2004).

If velocity tests are not done in the field during data collection, there are ways to estimate velocity in profiles if reflection hyperbolas can be found. One way is to use the theoretical geometry of a hyperbola. This can be done manually using a simple equation (see Bevan 1998), or with computer software. Another method, which can be used in conjunction with hyperbola fitting, is iterative migration. Migration is a data processing method that attempts to correct for the geometrical distortions inherent in GPR data due to the wide angle of transmitted waves and velocity changes, which also change the angle of incident waves (Conyers 2004; Mussett and Khan 2000). Velocity must be known to perform migration. Since a spherical (or similar) object produces a hyperbolic reflection, then migration using the correct velocity should result in a reflection that mimics the size and location of the top of the sphere, thereby removing the hyperbola

tails. If a series of migration tests are performed using different velocities, the one that produces the most accurate result can be assumed to represent the average velocity for the ground between the surface and the hyperbola's apex (Leckebusch 2003). This is a very fast and effective way of estimating velocity, and can also be used as a way of verifying velocity calculations from field tests. All that is needed are a few reflection hyperbolas. One potential problem is that if the ground surface is not located correctly in the reflection profile, velocity calculations of any sort will be incorrect (Ernenwein 2006).

Advantages and Disadvantages. Ground Penetrating Radar is one of the most complex of all the commonly used geophysical methods in archaeology. It takes more time to understand this method, learn how to set it up in the field, and to process and interpret the data. It is not very sensitive to magnetic features, such as those detected with magnetometry and MS. Yet there are several advantages that make this method a great addition to the suite of geophysical tools, and in some cases, the best and only viable method. In many cases GPR has greater depth penetration than most other methods (resistance, conductivity, MS, and magnetometry), and is much higher resolution. It is ideal for most ground conditions, with the exception of very wet clay or saline environments. It is also unaffected by scattered metal debris such as pin flags and shell casings. GPR can also provide critical depth information, something that can be only crudely estimated with other geophysical methods.

3. ESTIMATING A SITE'S SUITABILITY FOR GEOPHYSICAL SURVEY

It is generally not possible to predict with great certainty that a geophysical survey of a site that has not been previously investigated will be fully successful. It is possible, however—and very worthwhile—to assess the likelihood for success or failure based on a careful consideration of the relevant factors. Understanding those factors is the focus of this chapter.

A site's suitability for geophysical survey can be estimated by systematically addressing six issues, presented here as questions. The likelihood of survey success can be estimated based on the number of questions that are answered yes, probably, maybe, or no. If the answer to any one of these questions is a clear "no," then there is little point in moving forward with the survey. If the answers, however, are "maybe," "probably," or "yes," then the site should be considered at least partially suitable for geophysical survey. For example, if the worst answer to any question is "maybe," then a geophysical survey is questionable, but certainly feasible and deserving of further consideration. If all answers are "yes" or "probably," then the site is a prime candidate for geophysics. Once the site is judged suitable, the reader can proceed to Chapter 4, which provides guidance for choosing which geophysical methods might be best suited to the particular site.

3.1 Are archaeological features likely to be present at the site?

It is generally inadvisable to conduct geophysical surveys unless there is reason to assume that discrete subsurface deposits are present. These deposits may include features (e.g., pits, hearths, architectural remains) or larger deposits like midden lenses. Obviously the answer to this question is often unknown. Perhaps the best way to approach this question is to ask if intact cultural deposits would likely be discovered by a fairly intense subsurface testing program such as mechanized removal of the topsoil and/or plow zone. When possible it is advisable to consult with someone experienced in both geophysics and archaeology. Geophysical sensors can detect many, but not all types of features. The fact that geophysical surveys cover large areas with much higher sampling densities than shovel test pits, widely spaced test units, or other forms of exploration means that the sparse feature distributions may be more likely to be detected with geophysics. On the other hand, a site with abundant artifacts but no sizable features would be difficult to evaluate with geophysics. Whatever the case, if the probability of buried archaeological features is low, then the usefulness of a geophysical survey is also low.

3.2 Do the archaeological features have enough contrast with the surrounding matrix?

Contrast refers to a difference in physical properties between a subsurface archaeological deposit and the surrounding soil (as discussed in section 2.2) (Somers, et al. 2003). During excavation, archaeologists rely on visual and textural contrasts to differentiate cultural features from the surrounding soil matrix. The same features often have contrasting physical properties including soil compaction, moisture retention, artifact contents, and relative abundance of organic and burned materials. These characteristics — familiar to all archaeologists — are correlated with several geophysical properties (including magnetism, electrical resistance, and ability to reflect radar energy) that can be measured with great precision (Kvamme 2003; Scollar, et al. 1990). Features that contrast sufficiently with their surroundings in one or more of these properties can be detected in a geophysical survey conducted using an appropriate sensor. Note, however, that the strength of the contrast can be highly variable from site to site. This variability depends upon such factors as the local soils, moisture, bedrock and rock inclusions in the soil, as well as the nature of the archaeological features—their size, shape, and the nature of their fill.

Just because an archaeological feature is highly visible when excavated does not mean it will be characterized by a high contrast geophysical anomaly. Likewise, some geophysical anomalies that are, by virtue of their distinctive size or shape, almost certainly associated with subsurface cultural features are, upon excavation, invisible by sight and touch. When geophysical data are compared to excavation findings, there are four possible outcomes. Ideally the excavation will reveal a feature consistent with the geophysical data. Figure 15 shows a clear example of this, where three independent geophysical data sets show a rectangular anomaly and excavations revealed a high contrast pit house basin. Additionally, confidence in the reliability of decisions about site treatment is greatly strengthened when areas devoid of geophysical anomalies are also found to be sterile when excavated. Sometimes, however, there is a disagreement between the two sources of information (geophysical data versus excavations), due to the disparity between human senses and geophysical instruments with respect to the ability to detect archaeological features. Excavations sometimes reveal archaeological features that were not detected with geophysics even though nearby, seemingly similar anomalies may be clearly associated with visible features. In other cases, excavations may fail to explain why an anomaly exists. This is perhaps the most difficult finding to interpret because there are several plausible explanations. The anomaly could conceivably represent an error due to instrument malfunction or operator error. Often, however, anomalies are created by non-archaeological phenomena such as rodent holes, dips in soil strata, or ruts in the ground surface. Such phenomena are easily overlooked by archaeologists, particularly when their attention is focused on the search for cultural features rather than for any potential explanation for the anomaly. Third, the anomaly might indicate an archaeological feature that is not visible to the human

eye. Figure 16 shows one such case, where GPR data clearly show a rectangular house feature, but no evidence for it was found in the excavation unit. In this case, the excavations were conducted by archaeologists with substantial field experience in the region. This house floor may have been so clean that it did not leave a soil stain. Alternatively, the floor itself may have been eroded away and the GPR reflections are from sub-floor compaction.

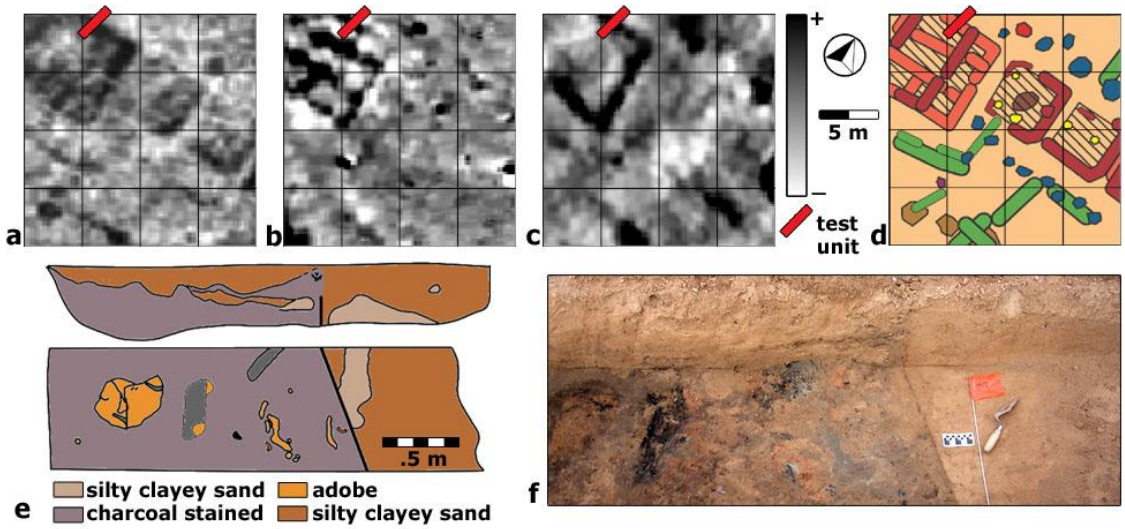


Figure 15. Testing of a rectangular anomaly at Pueblo Escondido, NM revealed a heavily burned pit structure. Geophysical data and the interpretive map for the surrounding area are shown: a) GPR slice from .47-.63 m, b) magnetic gradiometry, c) MS, and d) vector interpretation made prior to excavation. e) Profile of the test unit's west wall and plan map of trench floor (adapted from Lukowski, et al. 2006). f) Photograph of central portion of the test unit's floor and wall.

3.3 Are the archaeological features large and shallow enough to be detected?

For all methods discussed here (see Chapter 2) the likelihood of detecting a feature decreases with the feature's depth below surface (technically, distance from the sensor). There are configurations for most methods that can allow deeper penetration, but this is always at the expense of spatial resolution and does not always work. Table 1 provides penetration depth estimates for commonly used instruments. Section 4 describes the ability of the main methods to detect various types and sizes of features.

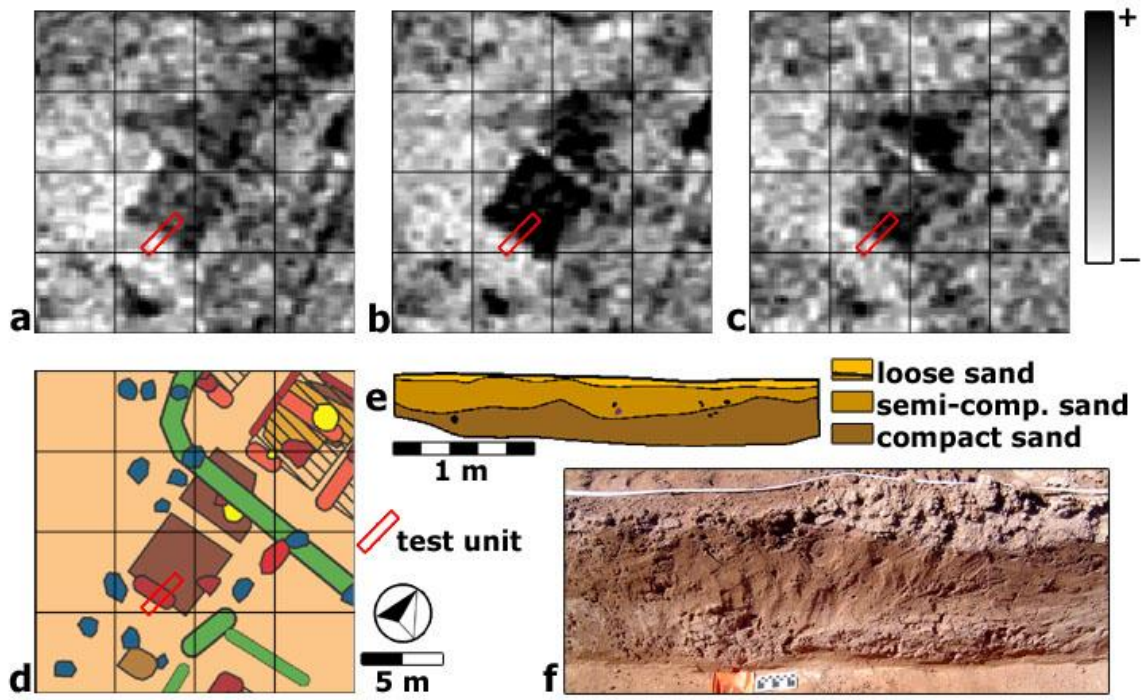


Figure 16. An example of a distinct anomaly—almost certainly a pit house—for which no evidence was found by excavation. Geophysical data and the interpretive map for the surrounding area are shown: a) GPR slice from .15-.31 m, b) GPR slice from .31-.47 m, c) GPR slice from .47-.63 m, and d) vector interpretation. e) Profile showing stratigraphy (adapted from Lukowski, et al. 2006). f) Photograph of the test unit's west wall.

Table 1. Approximate depth penetration for several different instruments

Method	Instrument	Depth (m)
Resistivity	RM15 or similar, twin probe array, .5 m separation	0.5
Resistivity	RM15 or similar, twin probe array, 1 m separation	1
EMI	EM38, conductivity, vertical mode	1.5
EMI	EM38, conductivity, horizontal mode	0.75
EMI	EM38, magnetic susceptibility, vertical mode	0.5
EMI	EM38, magnetic susceptibility, horizontal mode	0.25
EMI	EM31, conductivity, vertical mode	6
EMI	EM31, conductivity, horizontal mode	3
EMI	EM31, magnetic susceptibility, vertical mode	2
EMI	EM31, magnetic susceptibility, horizontal mode	1
Magnetometry	Fluxgate (Bartington, Geoscan, or similar)	1 – 1.5
GPR	GSSI system with 200 MHz antenna	3 – 7
GPR	S&S system with 250 MHz antenna	2.5 – 6.5
GPR	GSSI system with 270 MHz antenna	2 – 6
GPR	GSSI system with 400 MHz antenna	0.5 – 4
GPR	S&S system with 450 MHz antenna	0.5 – 3.5
GPR	S&S system with 500 MHz antenna	0.5 – 3
GPR	GSSI system with 900 MHz antenna	0.2 – 1

As a general rule of thumb, objects smaller than about .25 - .30 m will not be detected by geophysical methods with the exception of magnetic materials. Any object that is strongly magnetic (iron, steel, nickel, magnetite, any ferromagnetic material), even if very small (coin-sized), can be detected with a magnetometer (and sometimes EMI) if buried in the upper meter or so of earth. In a total field magnetometer survey, larger mass magnetic objects can be detected at greater depth; this is much less true in gradiometer (magnetic field gradient) surveys. This can be a great advantage at historic sites in the U.S. where iron artifacts are important. It can also be a problem because litter in the form of bottle caps, shell casings, and pin-flags are often found at archaeological sites and can be mistaken for historic artifacts or will obscure more subtle archaeological features. If time permits, a metal detector survey can be used to find and dispose of this kind of magnetic trash prior to a magnetometer survey. Note, however, that metal detectors have a relatively shallow depth of penetration, so abundant magnetic trash that is distributed throughout the plow zone can represent an essentially insurmountable problem for magnetic surveys.

Another general rule is that objects between about .3 and .5 m in diameter can be detected with geophysics, but only if they are buried less than 1 meter in the ground, and if sampling densities are high. For example, in favorable conditions for GPR, very small features can be detected using three or four transects per meter with a 400-500 MHz center-frequency antenna. In fact, with almost any method, features in the .25 - .50 m size range could possibly be detected using high sampling densities.

Small features present a challenge in geophysics because the associated anomalies typically do not exhibit a distinctive shape. Just because they can be detected does not mean that they will be recognizable as cultural features in the geophysical data. Shape is very important for interpretation, and small “blobs” (amorphous anomalies) in the data are often associated with rodent holes, pot holes, root disturbances, rocks, or any number of other anomalies caused by data collection errors or ground irregularities (Figure 17b). If small features are arranged in coherent (i.e., clearly non-random) patterns (Figure 17a), such as straight or curved lines of post holes along a wall or palisade, or circular arrangements of storage pits around a house, then they have a much greater probability of being recognized as cultural. When geophysical data contain nothing but amorphous anomalies then a more systematic method of interpretation is called for. Hargrave (2006) suggests categorizing the anomalies based on their dimensions, amplitude (data value), discreteness, sign (positive or negative), location relative to other anomalies and site characteristics, and by which geophysical sensor(s) detected them. Systematic excavations of a sample of each anomaly category may reveal correlations between different types of anomalies and buried cultural features versus anomalies arising from clutter. Where such correlations are detected, ground truthing results can be extrapolated (always with some degree of error) to uninvestigated anomalies.

Reasonably high contrast features measuring .5 m or more in diameter are more promising targets for geophysical survey, but the overriding factor is contrast. High contrast features can generally be detected at greater depth, but very low contrast features may not be detected even when very shallow. The ability to make predictions

about feature detection improves with experience, but remains difficult because so many factors (feature size, shape, contrast, soil, moisture, vegetation, etc.) contribute to a feature's potential to be detected. Some GPR simulation programs allow the user to draw the suspected feature in profile and give it relative dielectric permittivity values based on estimates of the material type (Goodman 1994). A GPR reflection profile is then simulated by running a virtual antenna over the drawn stratigraphic profile. This can be done to assess a feature's potential to be detected, and also to see what the reflections might look like given complicated geometry. Anomaly characteristics can also be calculated for other methods using fairly simple equations. Knowing the magnetic moment and volume of an object, and its distance from the magnetometer, the magnetic field strength can be estimated (Witten 2006). Similarly, knowing the depth, size, and conductivity/resistivity of a feature and of the surrounding materials allows the magnitude of the response with EMI instruments and resistivity meters to be predicted (Witten 2006). These kinds of calculations are helpful, but unfortunately they rely on estimates of the feature's volume, physical properties, and depth. It is rare that these details are known and they are very difficult to estimate. Modeling the geophysical response to unknown features is therefore not a reliable way to predict the success of a survey. It is helpful, however, to aid understanding of what is detectable versus what is not with the available sensors.

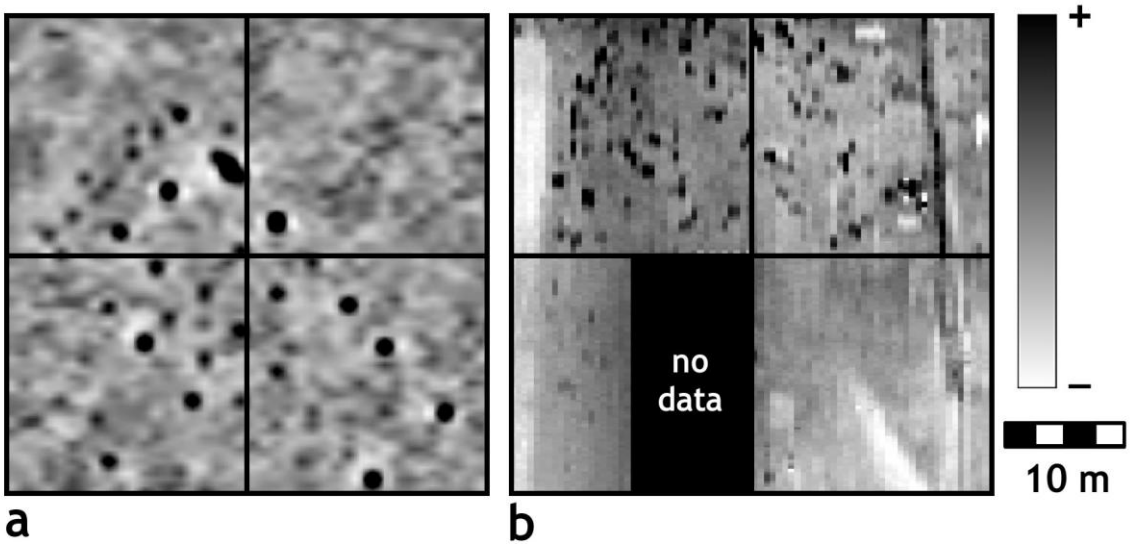


Figure 17. Systematic versus random small anomalies. (a) Concrete building footers from a historic structure at Army City, KS (see Kvamme 2006a) make a clear rectangular pattern in resistance data (from a Geoscan RM15), (b) but the random small anomalies in this MS data set (from a Geonics EM38) are much more difficult to interpret. They are probably related to small rocks and rodent holes on and near the ground surface.

3.4 Will the archaeological features stand out from clutter?

If features are large enough, shallow enough, and have sufficient contrast to be detected, they can still be difficult or impossible to recognize if they are obscured by clutter. Subfloor pits, for example, might have geophysical properties very similar to abandoned (in-filled) rodent burrows or tap roots. Clutter refers to anomalies in the geophysical data that are not related to the phenomena of interest (that is, archaeological deposits) (Conyers and Goodman 1997; Somers, et al. 2003).

Recent metallic trash is one of the most common and frustrating sources of clutter that can adversely affect a geophysical survey (Gaffney and Gater 2003; Kvamme 2001). Metal is particularly common on military installations and sites near modern or historic habitations. Clutter associated with ferrous metal is most troublesome for magnetic surveys but it can also affect conductivity data (Clay 2006). Small bits of metal near the surface or larger, deeper pieces are often manifest by strong (often dipolar) anomalies that make it difficult or impossible to detect the far weaker indications of prehistoric features. Wire pin flags used by archaeologists are particularly troublesome (Figure 10a) and should not be used at sites where future geophysical surveys may occur. Similarly, nails or spikes used as datum points should not be left in or near excavation units, particularly if the remaining portions of features are present in the unit walls. In most cases, however, the effects of such objects are highly localized (Gaffney and Gater 2003).

Rocks can represent another significant source of clutter in a geophysical survey. In some areas, igneous and iron-rich rocks can pose problems similar to those associated with metallic trash. Abundant rocks and near-surface bedrock can also represent a significant source of clutter in resistance and GPR surveys (Kvamme 2001). Unless rocks are both magnetic and abundant, the use of geophysics should not be decided against simply because they are present. Other common sources of clutter include deep plow furrows, vehicle ruts, tree roots, and looter holes. Note also that historic artifacts and features can act as clutter if the primary objective of a geophysical survey is to detect anomalies related to prehistoric features.

3.5 Is the ground surface suitable for the passage of geophysical instruments?

All questions so far have addressed the suitability of the subsurface archaeological content, but the condition of the ground surface is also very important. Often fences, uneven terrain, and especially vegetation make survey difficult and more expensive. Many archaeological sites, particularly those in the eastern United States, are located in wooded or overgrown areas. Most surveys are conducted with instruments that automatically collect data at fixed time or distance intervals. Such instruments can be manually triggered, but this slows the pace of data collection. Trees and undergrowth frequently make it impossible for the surveyor to walk directly down the data collection

transect. One reading may need to be taken .2 m to the left of the tape, whereas a few meters later the surveyor may be forced to shift .50 m to the right of the tape. Unfortunately, when the data are processed, the software plots the values as if they were collected precisely along the traverse. The effect of dodging around obstacles is to introduce a potentially substantial amount of noise into the data. Maps made using such data may not be very accurate in terms of anomaly locations and shapes, and correcting the spatial inaccuracies can be very time consuming, if not impossible.

The extensive root systems associated with large trees pose additional problems for geophysical survey (Figure 18). In a magnetic survey, large roots that displace very iron-rich soils might be detected as weak negative anomalies. In most magnetic surveys, however, tree roots are invisible (Kvamme 2001). In resistance and conductivity surveys, a tree's root system may absorb much of the local moisture, causing large high resistance or low conductivity anomalies. Roots can be directly detected (due to differential reflectance of electromagnetic energy) by GPR (Kvamme 2001) (Figure 18). It is difficult to predict the extent to which tree roots and above-ground vegetation may compromise a geophysical survey. Sites characterized by relatively large, high contrast features (such as historic habitation sites) may be less problematic, whereas ephemeral prehistoric sites that include small, low contrast features may be highly compromised.

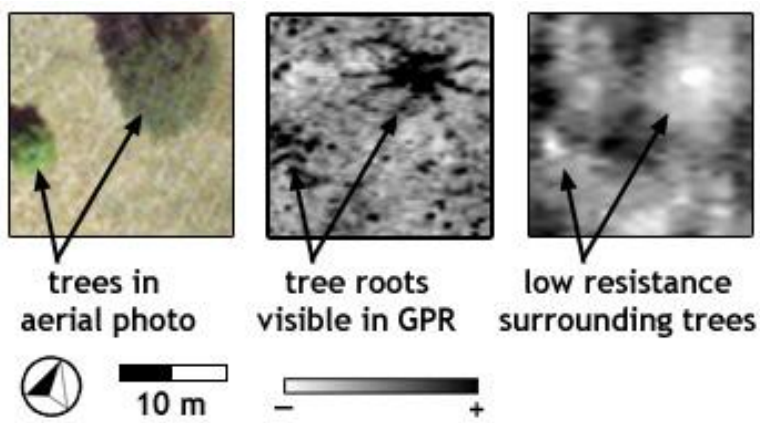


Figure 18. Effects of large tree roots on GPR and resistance data collected at Silver Bluff Plantation in South Carolina (see Kvamme, et al. 2006). The aerial photo shows the crowns of two trees that caused anomalies in GPR and resistance data. The GPR and resistance data were collected with a Sensors & Software PulseEKKO and a Geoscan RM15, respectively.

In non-wooded areas, tall grass, brush, and agricultural crops can also pose problems. The mowed grass found at many state and federally managed archaeological sites represents the ideal situation for geophysical survey. Unfortunately, this is rarely encountered in surveys associated with CRM projects. Agricultural fields where the crops have either not yet been planted or not yet grown high enough to make walking difficult can also represent excellent conditions for geophysical survey. Most often, however, tall grass, scattered bushes, and large rocks complicate a survey. In these situations a decision must be made whether to remove the obstacles or survey around

them, and whether to cut the grass. For GPR and EMI surveys, grass should be relatively short because the instruments must be moved along very close to or touching the ground. If necessary an EMI instrument can be carried higher, but this can place unwanted limits on depth and can be detrimental to MS data. Electrical resistance instruments are also much more difficult to move through tall, thick grass. Magnetometers can be carried through fairly tall grass as long as it does not impede the instrument or the surveyor as he or she walks. A magnetometer can be held above tall grass, although this is tiring, may introduce noise, and will significantly reduce the likelihood of detecting low-contrast features. Bushes can be removed, but care should be taken to cut them right at ground level rather than pull them out by the roots. The latter creates a great deal of disturbance and will very likely cause anomalies in the data. The same is true for large rocks or other objects. Removal should be done only if it does not create much disturbance. Removing a rock that leaves a large hole would result in data with an anomaly where the rock had been, whereas if the rock were kept in place there would be an area of "no data" or an anomaly from the rock

Other forms of surface disturbance include recent constructions such as fences, roads, pavements, and buried utilities. Often there is nothing that can be done to remove these types of disturbances, so certain geophysical surveys will be impacted. Any large metal object will be detected with a magnetometer. Fences are a common problem for magnetometry, often obscuring any buried features within several meters of the fence on both sides (Figure 19). Magnetometry is therefore seldom used in urban environments. EMI instruments have similar problems, though they are less sensitive to metal. GPR is commonly used in urban settings as it is not adversely affected by nearby, above-ground objects. Buried pipes and other facilities can complicate the detection of subsurface archaeological deposits. Data can be collected on pavement, and adjacent to fences or other large metal objects. Obviously probe-contacting electrical resistance data cannot be collected on pavement, so these areas are usually limited to GPR and sometimes EMI.

Another problem that fences and other large obstacles pose to all methods is obstruction of the regular gridded survey. When a fence runs through an area to be surveyed, the instrument must either be paused (if that is an option) and lifted over the fence for each line that crosses it, or a separate data set collected on either side, as was done for the magnetometry data set in Figure 19. The fence can also complicate the use of measuring tapes and survey ropes, so survey areas are difficult to set up and transects are more time consuming to plan.

The question of surface suitability can be a little difficult for novice surveyors, but the issues are more straightforward than those concerned with feature contrast. A rule of thumb is that if most transects of data can be collected without many obstacles, then the survey will be possible. In situations were there are many obstacles that cannot be removed or minimized, survey can still be done but it will take much more time and the results will be compromised.

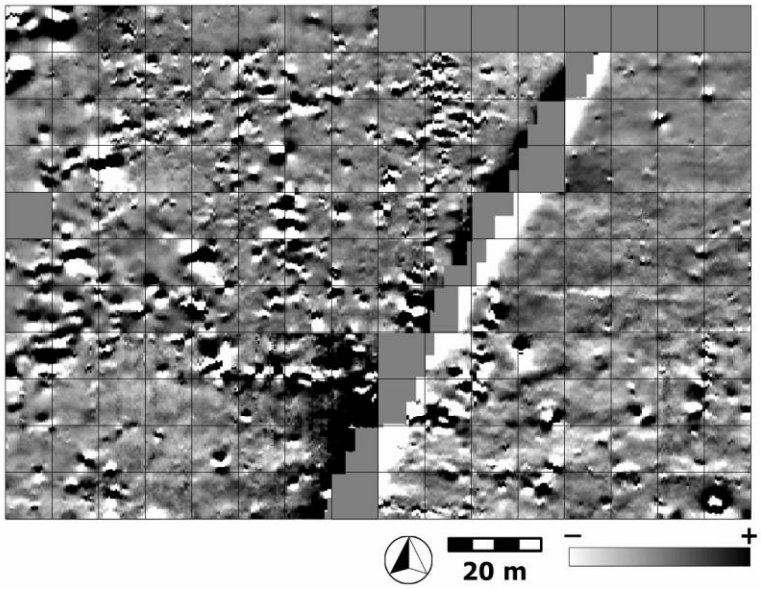


Figure 19. An example of surface disturbance caused by a chain-link fence. A tall chain-link fence runs through this magnetometry survey area at Tiwanaku (Bolivia), and the large induced field impacts data quality out to at least 5 meters on either side. These data were collected with a Geomtrics G-858 Cesium gradiometer.

3.6 Is the near surface suitable for geophysical investigation?

A final factor to consider is the amount of disturbance that has occurred to the near surface. Agricultural activities (plowing, disking) represent perhaps the most common type of near surface disturbance in much of the United States. The problems posed by plowing are, in many cases, relatively minor. Often only the uppermost layers of an archaeological site are affected, or they are not disturbed at all. In cases where the site is very shallow, however, the degree of disturbance by plowing should be taken into account. Some features that would have been “geophysically visible” become homogenized by plowing and are therefore invisible (Figure 20). Sometimes a survey can be set up to collect data parallel to agricultural furrows, which is preferred over walking across them. Collecting data over furrows makes walking difficult and often introduces unwanted periodic noise into the data. It is also best to survey fields long after their most recent plowing, as a well weathered and compacted surface permits more consistent walking. There is an exception, however, with resistivity surveying. Freshly plowed soil is soft and allows the probes to be inserted easily and to a consistent depth, and may make the readings more reliable. Another agricultural disturbance is related to livestock. Cattle can disturb the uppermost soil layer, which can create random noise in geophysical data (particularly magnetometry). Well established cattle-trails are likely to be visible as clutter in the geophysical data.

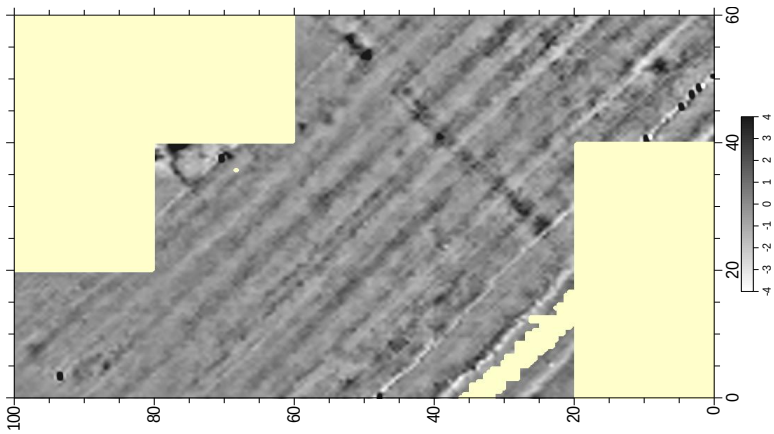


Figure 20. An example of near-surface disturbance by plowing. Plow ridges and furrows dominate this resistance data set from New Philadelphia, Illinois, making it difficult to see anomalies due to cultural features. Data were collected with a Geoscan RM15 resistivity meter. (from Hargrave 2007)

The effects of heavy construction equipment on the near surface can be detrimental to a geophysical survey. Sites where heavy equipment has been used extensively are often poor candidates for survey. This is especially true if the land has been leveled, if soil has been redistributed or brought in to fill depressions, or if portions of the area's topsoil have been stripped off. These create a situation where soil properties vary spatially, in places making cultural features invisible, in other places making them visible. In some cases leveling can actually remove part or all of the archaeological features. Repeatedly used haul roads are likely to be highly visible in a geophysical map (obscuring subsurface cultural features), as are the effects of sporadic cuts by a bulldozer or front-end loaders (Hargrave, et al. 2002). Experience by the authors has suggested that not all heavy equipment disturbances are detrimental to geophysical survey. The actions of heavy equipment seem to be most detrimental in situations where equipment use has been heavy but uneven, with some areas having been cut and others filled. A geophysical survey at Kasita Town (Fort Benning, GA) is a good example of the problems created by land leveling. Some portions of the survey area were covered by several centimeters of spoil (fill dirt, Figure 21), while other areas had been cut down, leaving features exposed very close to the surface. Dozens of excavation units plotted on the unfiltered resistance data reveal the impact of the leveling (Figure 22). The western portion of the survey area had been graded so that the Kasita Town living surface (which was located within the modern plow zone) was truncated. Areas to the east were preserved, but covered by up to .25 m of spoil. Only a small area in the northwest corner appears undisturbed by grading (Figure 22).

Conclusions. In summary, the following six questions can help determine if a site is suitable for geophysical survey: (1) Are archaeological features likely to be present at the site? (2) Do the archaeological features have enough contrast with the surrounding matrix? (3) Are the archaeological features large and shallow enough to be detected? (4) Will the archaeological features stand out from clutter? (5) Is the ground surface

suitable for the passage of geophysical instruments? And (6) Is the near surface suitable for geophysical investigation? If the answer to all six of the questions posed above is "yes," then the site is well suited for geophysical work. If the answer to one or more of the questions is "maybe," then the probability of a successful geophysical survey is more difficult to estimate. "Maybe" suggests that not enough information is available to answer the question so a geophysical survey should be approached with caution. If the answer to one or more of the questions is "no" or "probably not," then the site is not suitable for geophysical survey.

Figure 21. An example of near-surface disturbance caused by grading. A trench-wall at Kasita Town (Georgia) showing the plow zone and spoil from military grading of the survey area.

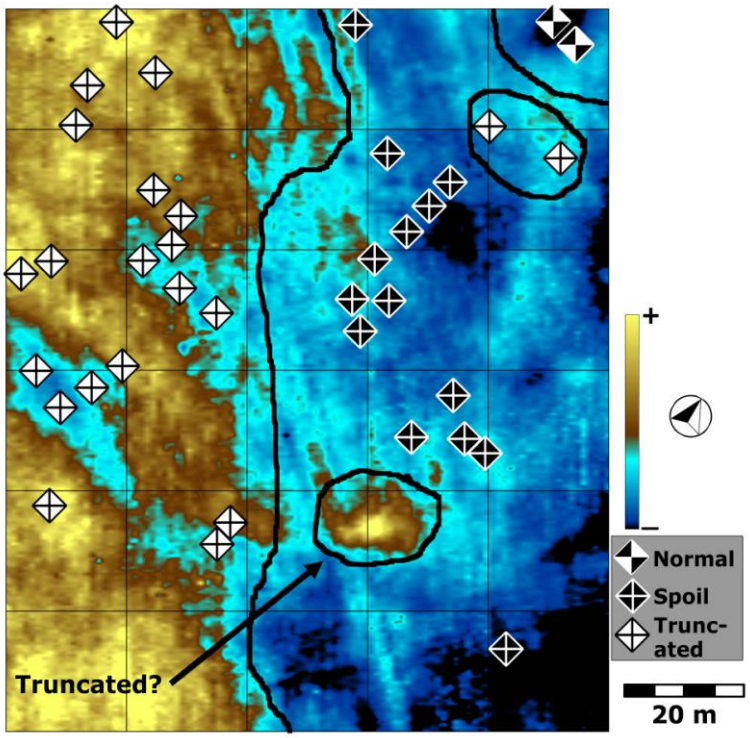


Figure 22. Map of cut and fill areas as a result of grading at Kasita Town, shown by electrical resistance data and excavations.

4. CHOOSING SUITABLE GEOPHYSICAL METHODS

If the questions posed in Chapter 3 indicate that a site is suitable for geophysical survey, the next step is to determine which methods to use. This typically involves a consideration of several factors. First, one should consider the practical limits on the survey in terms of the availability of equipment, funding, time, and expertise. One might, for example, have in-house access to several instruments but no funds to rent other instruments. Second, one must always consider how the site's physical characteristics (vegetation, disturbances, etc.) are likely to affect the use of each method. Finally, it is always important to consider the types of archaeological deposits that are expected to occur at the site, since these too will impact decisions about which methods to use.

Although we provide detailed guidance to help make informed decisions about which methods to use, the only sure means to determine if a particular method will be effective is to try it on a portion of the site. A modest sized area, perhaps 1,000 to 2,000 square meters or so should be surveyed with each of the available sensors to determine if any of them is suitable. If possible, trial surveys should focus on portions of the site where features have been previously documented (as long as they are not too disturbed by nearby excavations or looting). The following guidance is intended to help select the best methods for each situation, but keep in mind that even experts find it difficult to predict a survey's success, and it is wise to bring as many instruments as possible to the site. It is almost always desirable to investigate a site using multiple sensors, since this will increase the likelihood of detecting at least some features, and under favorable conditions, will increase the variety of features and other deposits that can be detected.

A good example of the benefits of using multiple instruments is the large survey conducted at Pueblo Escondido (New Mexico) by the authors and others (Ernenwein 2008; Kvamme, et al. 2006). On the first, relatively brief visit to the site four instruments were tested: GPR (a GSSI SIR2000 with a 900 MHz antenna), EMI (Geonics EM38B), magnetic gradiometry (a Geoscan FM36), and resistivity (a Geoscan RM15). All four methods were equally disappointing, showing only hints of possible structures and features, but no clear evidence (Figure 23). Yet, the survey was not abandoned because dense surface artifacts and previous excavations indicated that subsurface features (including adobe rooms and related features) were almost certainly present. All four instruments were brought back for the full survey some months later. The results of these surveys were dramatically improved, in part because a larger area was surveyed (one hectare), but also due to some slight changes in instrumentation and drier conditions, which were more favorable for GPR. Resistance could not be used effectively because of insufficient soil moisture, and conductivity data revealed only a few midden deposits. The GPR (this time using a 400 MHz antenna) (Figure 24) and MS data (Figure 25a) were both highly successful, revealing dozens of pit houses spread out over the entire survey area. Magnetometry data at first appeared to be rather uninformative until a few structures (later found to be burned pit houses) were detected on the last day of survey (Figure 25b). The success of the GPR was due mostly to the switch from a

900 to a 400 MHz antenna as well as the drier ground conditions on the second visit. Also, the second survey was conducted an area littered with pithouses and associated features, whereas the first survey may have been conducted over an area devoid of substantial features (we simply do not know). In the first author's experience, the 900 MHz antenna is of limited use at typical archaeological sites because it is sensitive to too much detail, therefore recording reflections from very minor soil changes and rocks which obscure reflections from slightly larger features that are more likely to be archaeological and easily identified based on their size and shape.

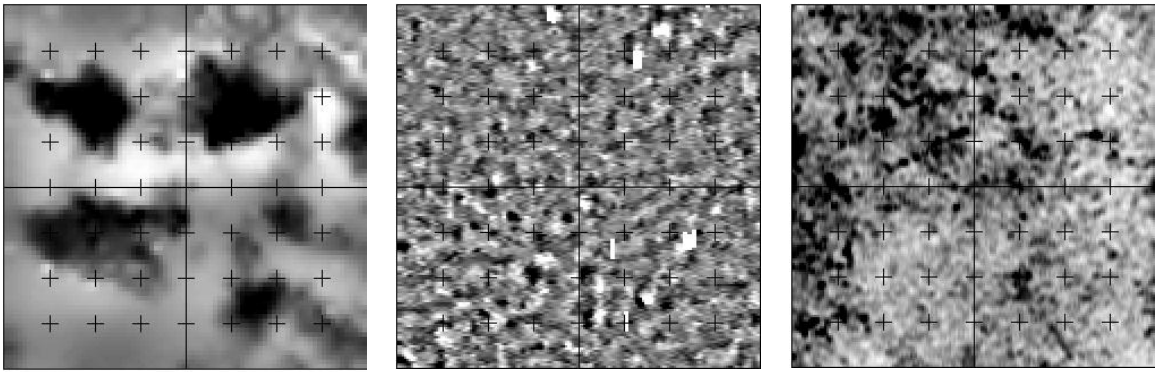


Figure 23. Results of the trial survey at Pueblo Escondido, Fort Bliss, NM (40 x 40 m area): (a) electrical resistance; (b) magnetic gradiometry; (c) ground penetrating radar 2-4 ns time slice.

4.1 Consider Practical Limitations

Dollar for dollar, a geophysical survey supplemented by small scale but thoughtful ground truthing often (but not always) provides far more information about a site than exclusive reliance on hand excavation. Despite this potential advantage in cost efficiency relative to information return, budgetary considerations constrain geophysical surveys, just as they do excavation programs. A primary issue is equipment availability. The ideal situation would be for all four of the main instruments (resistance, EMI, magnetometry, and GPR) to be available in-house for use. Many geophysical users, however, only own or have sustained access to one or two instruments. Renting instruments can be frustrating because of both the cost and the associated time constraints (instruments are often rented by the day or week), and the limited selection of instruments available for rent. For example, at the time of writing no resistance meters are available for rent (other than those designed for geology). If one's organization does not own a suitable resistance system, one must be borrowed from a friend or colleague, or purchased. Although the two most widely used brands of magnetometers designed for archaeology (Bartington and Geoscan fluxgate instruments) are also unavailable for rent, viable alternatives such as the Geometrics G-858 cesium vapor gradiometer can be rented. Fortunately the majority of electromagnetic induction instruments and GPR systems are widely available for rent.

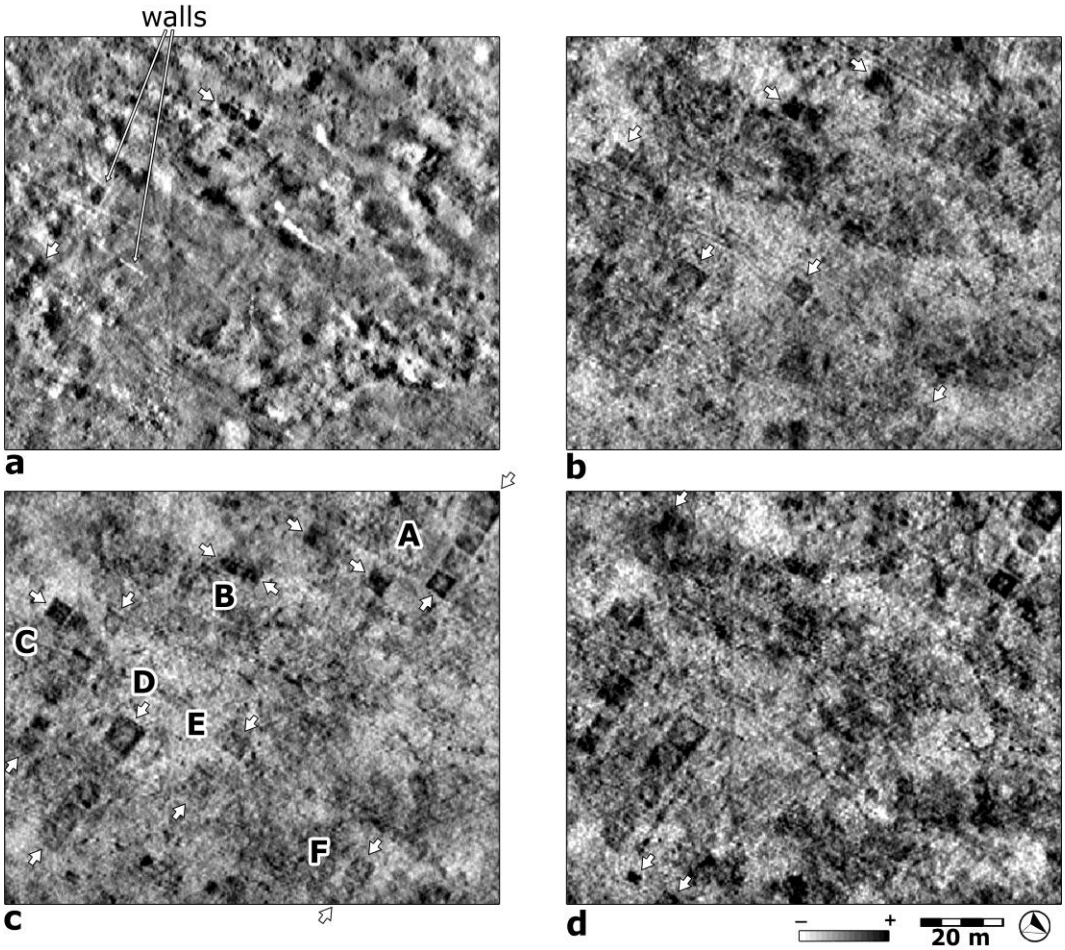


Figure 24. GPR depth slices from the final survey at Pueblo Escondido, Fort Bliss, NM: (a) slice 1, .09-.16 m, with short arrows indicating shallow dwelling; (b) slice 2, .15-.31 m, with arrows indicating some of the most clearly visible pithouses; (c) slice 3, .31-.47 m, with six household groups labeled A-F and diagonal arrows marking the ends of east-west and north-south structure rows; (c) slice 4, .47-.63 m, with some of the deepest archaeological features indicated by arrows. (see Ernenwein 2008)

Limitations in expertise also represent an important factor. Someone who has never conducted a GPR survey should not expect the fieldwork and subsequent analysis to be done in a timely and efficient way the first time. It is entirely possible that one's first survey will not yield usable data. Substantial practical experience is required for all methods, but especially GPR because it entails a relatively detailed field setup followed by more complex data processing. *ArchaeoMapper* is designed to make the use of GPR by beginners less daunting and more likely to be successful, but the learning curve is still a significant issue.

Finally, it is worth mentioning special circumstances that can preclude the use of certain methods. Individuals with surgical metal in their bodies cannot conduct a magnetometer survey if the metal is magnetic (some stainless steel is highly magnetic,

some is not). Using all of the instruments involves some physical effort, particularly extensive walking while carrying or dragging sometimes heavy instruments. Individuals with back, knee, or shoulder conditions, or other physical ailments should consider these issues prior to purchasing instruments.

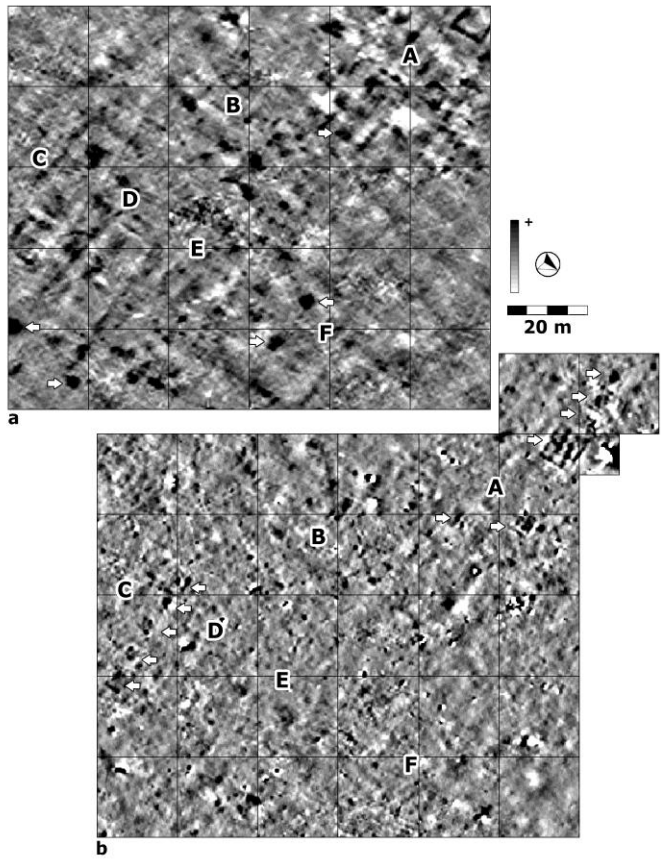


Figure 25. Magnetometry and magnetic susceptibility results from the final survey at Pueblo Escondido, Fort Bliss, NM: (a) MS, with possible pithouses indicated by horizontal arrows; (b) magnetometry, with probably burned houses indicated by horizontal arrows. The same six household groups used in Figure 24 are labeled A-F. (from Ernenwein 2008).

4.2 Consider Environmental Effects

Certain environmental conditions can be very beneficial for some methods but detrimental to others. The major environmental factors affecting the success or failure of a survey can be categorized into electrical and magnetic properties of the ground. Electrical properties, generally dictated by ground moisture and sediment texture, dramatically affect resistance, conductivity, and GPR. A less common factor, soil salinity, also dramatically changes ground conductivity and therefore affects electrical methods. The remaining two geophysical methods, MS and magnetometry, are very strongly

affected by the magnetic properties of the ground, rocks, and cultural features. The presence of metal debris on the surface, large metal objects such as signs or fences, and igneous rocks in the ground affect MS and magnetometry. The degree of soil development also has profound effects on survey success. Table 2 lists these properties and their effect on each of the five main geophysical methods. The effect of environmental conditions on the potential success of each method is rated as (B) beneficial, (N) no effect, (C) cause for concern, and (P) problematic. Each condition is discussed in detail in the following paragraphs.

Table 2. Effects of environmental conditions on common geophysical methods B=beneficial, C=causes concern, N=no effect, P=problematic.

Condition[1]	RES	COND	GPR	MS	MAG
extremely dry	P	P	C	N	N
dry	C	N	B	N	N
moderate moisture	B	B	B	N	N
Moist[2]	B	N	C	N	N
saturated	P	C	C	N	N
high % clay minerals	N	N	P	N	N
moderate to high salinity	N	N	P	N	N
abundant non-magnetic rocks	C	N	C	N	N
abundant magnetic rocks	C	N	C	N	P
magnetic bedrock near surface	N	N	N	N	P
metal (ferrous) debris on surface	N	C	N	N	P
large metal objects (fences, etc.)	N	N	N	N	C
poorly developed soils	N	N	N	C	C
well developed soils	N	N	N	B	B

[1]assuming soil has adequate magnetic contrast with the subsoil
[2]assuming the ground is still stable to walk across without much damage
RES=resistance; COND=conductivity; MS=magnetic susceptibility; MAG=magnetometry

Moisture, clay, and salt. The success or failure of methods that rely on electrical properties (resistance, conductivity, and GPR) is essentially dictated by the amount of moisture in the ground, which in turn is related to soil/sediment particle size (clay, silt, or sand), drainage, and climate. Fortunately, conditions at most sites are favorable for at least one method, even if unfavorable for others. The greatest concern with moisture levels occurs under extremely dry (little or no moisture in the ground), or fully saturated (swamp-like) conditions. In both cases all three methods may suffer because of lack of contrast. Contrast, as discussed in chapter 2, is a critical factor for all geophysical methods. Archaeological features can often be detected with electrical methods because they either retain moisture better than surrounding materials, or they drain more freely and dry out more quickly. Moisture is retained longer if a feature contains relatively finer-grained materials (compared to surroundings) or is not as well drained. Conversely, a feature might have better drainage and less moisture-retention ability, making it stand out against a wetter, more moisture retentive background. If the entire site is extremely dry, such that even the more moisture-retentive features or soils become dried out, then contrast is diminished and the features may not be detected

with electrical methods. Similarly, if the site is completely saturated the contrast might be very low and hide otherwise visible (detectable) features. Fortunately, excessive moisture is generally a temporary condition, since most sites that exhibit evidence of significant past occupation were not established in very poorly drained areas.

Ground moisture depends on three major factors: soil or sediment type, drainage, and climate. Coarse-grained sediments and soils, such as gravel and sand, are very porous and drain relatively freely, whereas silt, and especially clay, drain much more slowly, and are almost never completely dry. Particle size can therefore dictate moisture retention, and differences in grain size between archaeological features and the background sediments and soils is what makes them detectable with geophysical methods sensitive to electrical properties. In some situations, however, drainage plays a role. If drainage is very poor, then even coarse-grained, porous sediments will retain moisture for long periods after a rain event. A related situation is ground-water level, which fluctuates seasonally in many areas. Climate is another obvious factor, in that some areas are naturally much wetter than others during certain times of the year or year-round. Knowledge about the climate, sediment size, and drainage at a site can be used to partially predict the success or failure of geophysical surveys, particularly those that rely on electrical properties. A site situated in well drained, sandy soil with features having sediment-size contrasts, for example, should be surveyed shortly after a heavy or long-lasting rain event. In theory, the features would retain moisture while the surrounding sediments would drain and become relatively dry (or vice versa).

Resistance and conductivity instruments exhibit similar responses to moisture, although resistance surveys are more dependent upon adequate moisture because of the need to insert probes into the ground. The likelihood for a successful survey using both techniques is diminished by extreme drought or thoroughly wet conditions, which cause a lack of contrast. Usually, however, even very dry areas have some ground moisture and conductivity survey can reveal features to some degree. Resistance, however, requires enough moisture at the ground surface to allow probes to be inserted and currents to flow. In very dry conditions the resistance probes meet contact resistance (currents do not flow into the ground at all because electrical resistance is so high), preventing accurate measurement of deeper ground resistance (Clark 1996). In these cases EMI conductivity can be used. In moderate moisture and even fairly wet conditions, resistance and conductivity work well and often have good results if features have electrical (moisture) contrasts with their surroundings. The presence of clay has little ill effect on these two methods, unless it makes the ground so hard that resistance probes cannot be inserted. Salinity also has little effect on the ability to conduct these surveys and detect archaeological features, but it does make the conductivity of the ground quite high.

The effects of moisture, clay, and salt are most pronounced with respect to ground penetrating radar (GPR). The ability to detect features, as with the other methods, is strongly influenced by the amount of moisture contrast between features and the surrounding soils. Lack of contrast due to extreme drought or saturation of the soil can result in very weak or nonexistent reflections from buried features. It is rare that the ground is so dry, however, that adequate moisture is not retained, and GPR has been

very successful in many desert environments. All that is needed is a tiny bit of moisture to generate sufficient contrast in dielectric permittivity (Conyers 2004). In fact, GPR is often successful in very dry areas where moisture contrast is not high enough for resistance or conductivity. This is because GPR responds not only to electrical conductance, but to other factors contributing to the relative dielectric permittivity of materials (Conyers 2004), including soil compaction. As the moisture contrast between features and the background increases, the ability to detect them with GPR also increases, but there is another limiting factor. As moisture increases, GPR energy is increasingly attenuated, thereby reducing depth penetration. Moisture can therefore be both an enabling and a limiting factor for GPR. In dry and sometimes drought-like conditions depth penetration is optimal, but contrast is not. Given slight to moderate moisture, however, GPR reflections will be very strong while depth is not severely affected. In extremely wet conditions the majority of radar energy that enters the ground can be attenuated and never reach the receiving antenna.

GPR depth penetration also depends on the amount of clay and salts in the ground. Both clay minerals and salts (unless completely desiccated) are extremely electrically conductive, and can cause rapid attenuation and severely limited depth penetration. The limiting effects of clay are probably overemphasized in the literature and by some GPR practitioners, however, and this has probably resulted in many unnecessary decisions not to do GPR when the ground contains some clay (Conyers 2004). Some clays are much more conductive than others, and the amount and type of clay in the soil is difficult to determine without detailed soil tests. Sometimes clay limits the depth penetration to 1 - .5 m or even less, but this may still be adequate for detecting shallow archaeological features. Salinity is also highly variable. In some desert environments it is a problem (Conyers 2004), and certainly the presence of seawater in coastal areas can be problematic.

Rocks. The presence of rocks (and other hard objects such as clods of soil) on the surface and in the ground, particularly those larger than a baseball, pose a problem for some geophysical methods. For resistivity, rocks can obstruct the probes, cause erroneous readings, and represent clutter. Rocks not only represent clutter in GPR data, they also obscure deeper features by reflecting much of the energy before it reaches them. These problems occur no matter what types of rocks are present, but the problem is made worse by higher densities and larger rocks. If some of the rocks have remanent magnetic fields (e.g., igneous rocks), then they can be a major source of clutter in magnetometry data (Kvamme 2006b). Andesite, for example, is highly magnetic and each small piece will create a dipolar magnetic anomaly. The problem is much less severe if the rocks are only weekly magnetic or deeply buried.

If the local bedrock is shallow and highly magnetic, or if it contains veins of magnetic rock, these will pose a problem for magnetometry survey (Clark 1996; Kvamme 2006b). If the rock has a remanent magnetism, it may preclude the use of magnetometry, because there will be a constant, strong field throughout the survey area, which will be much stronger than any archaeological features. Rock that is not thermoremanent but has high MS due to its inclusion of magnetic minerals can also be a problem, depending

upon its magnetic strength, depth below surface, and the strength of its magnetic character relative to the archaeological features located above it. Only a trial survey can ascertain how serious such problems may be, but if one is aware that magnetic rocks or bedrock is present at a site, use of non-magnetic methods should assume higher priority.

Soils. Most soils are at least somewhat magnetic. Human activities enhance soil MS, therefore soil type and thickness and its contrast with underlying subsoil strongly influence the success of magnetometry and MS surveys (Clark 1996; Dalan 2006; Gaffney and Gater 2003; Kvamme 2006b). Archaeological features such as pits, ditches, and house basins were often filled with topsoil that washed in from the surrounding area. The concentration of magnetically enhanced soil in these features makes them contrast with their surroundings. In desert or other environments where soil development is minimal such features are more likely to be filled with nonmagnetic soil or sediment. Magnetic methods can also be problematic in deserts because of lag deposits of magnetic minerals that accumulate around shrubs and other objects (Clark 1996). Since magnetic minerals are usually heavier than other particles, they tend to be left behind as the wind redistributes sediments. Since the magnetic sediments are on the surface they are readily detected with a magnetometer (because they are so close to the sensor) and can create anomalous readings that add a great deal of clutter (Clark 1996).

Despite these potential problems, magnetometry and MS can be successful in desert and other environments with weakly magnetic soils. Magnetometry will detect thermoremanent features such as hearths and burned houses, and MS measured with EMI may be more sensitive to subtle variations in MS than a magnetometer. Magnetometry and MS data collected at Pueblo Escondido, located in the hot, dry Tularosa basin of southern New Mexico, make a prime example. Magnetometry data collected with a Geoscan FM36 fluxgate gradiometer revealed several heavily burned pithouses (Figure 25b), but detected no signs of the many other dwellings that were unburned (shown by GPR in Figure 24). Many of the pithouses, both burned and unburned, were detected by MS survey using an EM38 (Figure 25a). The MS maps also show linear patterns surrounding the pithouse rows, which are interpreted as informal patios (Ernenwein 2008).

Metal objects and debris. Metal objects of all sizes and shapes represent a problem for some types of geophysical surveys, most notably magnetometry, but also conductivity. Surveys at many sites are complicated by large metal objects of one sort or another, including fences, pipelines, culverts, signs, and survey markers. Magnetometry surveys are most strongly affected by these, while other techniques are more mildly affected. Unless they cover much of the site, however, large metal objects are not too much of a concern because they are localized. A more serious problem is often created by metal debris scattered about the ground surface. Often sites are littered with bottle caps, military debris, and metal pin flags from previous archaeological surveys. Each small piece of ferrous metal can create a disproportionately large anomaly in

magnetometry data, obscuring nearby archaeological features. In EMI conductivity survey, metal objects on or near the surface create a series of readings – very high, then very low directly over the object, followed by very high again (for an explanation, see Burger, et al. 2006). The high-low-high signature can be a benefit for locating historic artifacts or other metal that is of interest (Bevan 1998; Heckman 2005), but also a source of clutter if associated with recent metal debris (Clay 2006). If a site is littered with metal debris it should be cleared before magnetometry or EMI survey, which sometimes requires a systematic metal detector survey. Note, however, that removal of metal debris may not be practical in situations where the metal is distributed throughout the plow zone.

Summary. When choosing which geophysical methods to use, environmental effects are probably the most important factor to consider. Ground moisture, along with sediment size, drainage, clay content, and salinity, can determine the success or failure of resistance, conductivity, and GPR. Table 2 can be used to determine which methods are best suited given the environmental conditions that characterize a particular site. If conditions are dry and desert-like, the best method is probably GPR, followed by EMI. As moisture increases, GPR is still a good choice but depth penetration could be more limited. Resistance and conductivity are excellent choices when moderate to ample moisture is present. As conditions approach saturation, however, GPR becomes more limited in depth penetration and all three methods suffer from lack of contrast. As the percentage of clay minerals increases, conductivity increases and this can put serious limits on GPR depth penetration, but conductivity survey is barely affected and resistance surveys are also promising as long as the clay does not prevent probe insertion in to the ground. If sea water or other electrolytes are present, GPR will be greatly limited.

In the case of magnetic methods, environmental conditions are less important. Moisture, sediment size, and salinity play almost no role. It is the thickness and magnetic richness of topsoil relative to subsoil (i.e., the contrast between the two), as well as the magnetic properties of local and imported rock that dictate the success of magnetic methods. If soil is magnetically enriched compared to subsoil, magnetic methods are more likely to be successful (Clark 1996). Keep in mind, however, that MS is very sensitive, and has been found to work well even in desert environments (Ernenwein 2008). Magnetometry is also useful in environments with very weakly magnetic soils because it measures remanent magnetic fields, which are often created by burned archaeological features (Figure 25b) and features that include magnetic rock. Overall magnetometry seems to work well in most environments in North America (Kvamme 2006b). The potential to detect various types of features is discussed in the next section.

4.3 Consider the Nature of Archaeological Features

One very important factor that has not yet been discussed is the nature of the archaeological features and other deposits likely to be present at the site. Even if the environmental conditions are very favorable for certain methods, the features present at the site may simply not exhibit sufficient contrast with their surroundings to be detected. Table 3 lists several different types of features, the feasibility of detecting them with the various methods (rated as Poor, Moderate, or Excellent), and a brief explanation. In all cases, feature types are very generalized and many assumptions are made. Our focus here is on the most common types of features. For example, most post holes are quite small (generally less than .30 m in diameter in the authors' experiences), so this size range is assumed in Table 3. Isolated post holes, if detected, would be difficult to recognize as cultural features. Post holes arranged in linear or other coherent patterns would, of course, be more readily identified as cultural. Table 3 also assumes that the features in question are not too deep to be detected, and that the site's environmental conditions are reasonably favorable for that method. This is why the feasibility of detection is rated as "poor" for very few of the feature types. Each of these features is discussed in detail in the following paragraphs.

Pits and Excavations. This category includes features that were created by the removal of earth and subsequent infilling, resulting in features that contrast with the surrounding matrix. These features include post holes, graves, old archaeological excavation units, various types of prehistoric and historic pits (storage, processing), borrow pits, house basins, privies, cisterns, wall trenches, incised pathways, and ditches. Magnetic methods work well for detecting pits and excavations when topsoil was removed and either not replaced, or replaced in a different order than the original strata (as with some graves) (Kvamme 2006b). Both cases result in negative magnetic anomalies. Such features would be manifest as positive magnetic anomalies if they were eventually filled with soils that are, because of their organic, artifact, or burned soil contents, more magnetic than the surrounding soil. Pits and excavations can also be detected with resistance, conductivity, and GPR when conditions are favorable. Often pit fill is less compact than surrounding materials, allowing good moisture contrast due to differences in water retention. Radar waves may reflect off the boundaries of pit features, including the sides and bottom if not too deep. In well stratified soils an excavation is represented by a break in horizontal reflectors, which is visible in reflection profiles and sometimes in time slices.

Very small pits and excavations such as post holes, small (non-extended) burials, old shovel-test pits, and other small pit features are very difficult to detect with geophysics. They are usually too small, do not occur in recognizable patterns, are easily confused with clutter, and may lack sufficient contrast with surrounding materials. Grave detection has received some focus in the literature because of the potential of geophysical method to locate unmarked graves without excavation. The vast majority of successes in the area, however, are with historic or very late prehistoric graves because

they are larger than most prehistoric (e.g., flexed) burials and sometimes contain coffin remains (Bevan 1991; Conyers 2006b; Kvamme 2006b). Even historic cemeteries are challenging, however, owing to the density of surface obstacles and magnetic clutter. Old archaeological excavations are similar to graves in their typical size (1 x 1 – 1 x 2 m), and are also difficult to detect most of the time. If very small pits or excavations are sought, data should be collected at a much higher than typical data density that insures the features will be sampled several times in both directions.

Table 3. Feature detection feasibility for common geophysical methods (P = Poor, M = Moderate, E = Excellent)

Feature	RES	COND	GPR	MS	MAG	Explanation/Notes
Pits/Excavations:						
Post hole	P	P	M	P	P	Generally too small, often no patterns
Grave (no void space)	M	P	M	M	M	Small, low contrast, may lack pattern
Excavation (archaeological)	M	M	M	M	M	COND often blurs boundaries
Processing/storage pit	P	P	M	M	E	Often small, low contrast
Borrow pit	M	M	M	E	E	Usually a soil (magnetic) low/void
House basin	M	M	E	E	E	Favorable compaction, fill, size & shape
Wall trench	M	M	E	M	M	Favorable shape/pattern
Pathway	M	M	E	M	E	Favorable compaction & incision
Ditch	M	M	M	M	E	Often good contrast & patterned
Void space (graves, tunnels)	P	M	E	M	M	Voids are very good GPR reflectors
Walls:						
Adobe/mud wall	M	M	E	M	M	Depends heavily on contrast
Stone wall, non-magnetic	E	E	E	M	M	Magnetic contrast questionable
Stone wall, magnetic	E	E	E	E	E	Electrical & magnetic contrast
Brick wall	E	E	E	E	E	Electrical & magnetic contrast
Monoliths						
Non-magnetic stone	M	M	M	M	M	Lack of pattern
Magnetic stone	M	M	M	M	E	Assuming remanent magnetism
Floors/pavements/surfaces:						
Compact earthen surface	P	M	E	P	P	Favorable compaction & contrast
Prepared mud/adobe surface	M	M	E	P	P	Favorable compaction & contrast
Stone floor, non-magnetic	E	E	E	P-M	P-M	Magnetic contrast still possible
Stone floor, magnetic	E	E	E	M	E	Nature of magnetic contrast varies
Artifacts:						
Ferrous metal	P	M	P	P	E	Must be very shallow for COND
Igneous rock (small)	P	M	P	P	E	Must be very shallow for COND
Fired/Burned Features						
Hearth, small/unprepared	P	P	M	P	M	Lacks size, robustness, & pattern
Hearth, prepared	P	P	M	P	E	Favorable compaction, burning, size
Kiln	M	M	E	M	E	Favorable size, burning
Very large clay pot	P	P	M	P	M	Remanant magnetic field from firing
Burned house/architecture	M	M	M	M	E	Favorable size, pattern & burning
Accumulations:						
Midden	E	E	M	M	M	Favorable moisture contrast
Earthen mound	E	E	M	E	M	Moisture and magnetic contrast

RES=resistance; COND=conductivity; MS=magnetic susceptibility; MAG=magnetometry

Pits and excavations that are larger or have more formal geometric arrangements are more likely to be detected than small features because they stand out from clutter. Common examples are house basins, wall trenches, and large borrow pits. Borrow pits often create negative magnetic anomalies due to topsoil removal. Their fill may also differ from the surrounding sediments, creating an electrical contrast. House basins are more readily detected if they have compacted floors and contain features and cultural debris. In addition, they are sometimes associated with wall trenches that stand out as straight lines in geophysical maps. Other linear features, such as pedestrian pathways and ditches, are also created by excavations. Pedestrian pathways are often incised into the surface, displacing topsoil to the sides and therefore making magnetic anomalies (Kvamme 2006b). Ditches created for defensive purposes, irrigation, or other uses, are sometimes found at North American sites. These too are created by the removal of topsoil and are often quite deep, making them detectable by magnetic and sometimes electrical methods if their fill contrasts with the surrounding matrix (e.g. Kvamme 2008).

Walls. Walls are common archaeological features, and are favorable for geophysics because they exhibit a distinctive geometric shape. Long straight anomalies arranged at right angles to each other, or in circles or ovals are easily recognized as walls in geophysical data. In the southeastern US, daub (fired clay) walls are often highly visible in magnetic data. Walls made entirely of unfired mud or adobe are best detected with GPR, but can also be located with any geophysical method if thick enough and if the surrounding materials provide enough contrast. The situation is improved if the foundations or the entire wall is made of stone, because stone often contrasts with surrounding soils both electrically and magnetically. In some cases stone walls create negative magnetic anomalies if the surrounding sediment or soil matrix is significantly more magnetic that the rock itself. When walls include igneous rocks, or any kind of rock with a thermoremanent magnetic field, then each stone will show up as a relatively strong anomaly in magnetometry data. Brick walls are very similar, because bricks acquire thermoremanent fields when they are heated during manufacture (Bevan 1994).

Monoliths. Monoliths (which are rare or absent in the US prehistoric archaeological record) can be detected with most geophysical methods, but recognizing them as archaeological features would be problematic if they do not have a distinctive shape or occur in a pattern such as a series of monoliths marking a boundary or some other alignment. A large stone (e.g., a grinding or “nutting” stone) in general can be detected with resistance, conductivity, and GPR, but detection with magnetic methods depends on the magnetic contrast between the rock and surrounding materials. If the rock is considerably more or less magnetic than the surroundings (in terms of MS), then it could be detected by either magnetic method. If it possesses a remanent magnetic field, then it will be very easily detected with a magnetometer. There is, however, no simple relationship between the apparent dimensions of a magnetic anomaly and the actual dimensions of its source.

Floors, Pavements, and Surfaces. A compacted surface may be visible with ground penetrating radar because the abrupt change across the interface will usually cause a strong (high-amplitude) reflection. Detection of such a surface with resistance or conductivity will depend on the contrast in materials above and below the surface, or of the surface itself if thick enough. Sometimes a surface will create a moisture boundary, causing greater moisture retention immediately above it compared to surrounding areas where the surface does not extend. Surfaces made of stone are more likely to be detected by all methods, because stone often creates both an electrical contrast (mostly due to moisture differences) and magnetic contrast if the stone is significantly more or less magnetic than the adjacent materials. As with many other types of features, if magnetic stone is present it will be highly visible with magnetometry, especially if the rock has a remanent magnetic field.

Artifacts. Artifacts are not usually a realistic target for geophysical surveys unless they are quite large. The exception is artifacts made of ferrous metal or otherwise magnetic materials. At historic sites a great variety of artifacts are made with iron, including construction materials, tools, machinery, buttons, cookware, and military munitions. These can sometimes be detected with EMI conductivity, but only if the instrument comes into very close contact with the artifact (Bevan 1998; Heckman 2005). Much better results are acquired with a magnetometer, which senses the strong thermoremanent magnetic fields for each artifact. This can be a benefit at historic sites, but if too many artifacts are present they tend to obscure other non-ferrous features. At sites with both prehistoric and historic components, magnetometry data will be dominated by the ferrous historic artifacts and not very effective for mapping the prehistoric features.

Fired or Burned Features. Features that burned (house walls and floors, hearths, earth ovens, etc.) are far more likely to be detected using magnetic and MS methods, but only somewhat more likely than unburned features to be detected using resistance, conductivity, or GPR. As discussed in section 2.2.4, when materials are heated to very high temperatures they acquire a remanent magnetic field, which can be detected with a magnetometer (Kvamme 2006b; Tite 1972). The more a material is heated, the more magnetized it can become (Tite 1972). Burning also enhances MS (Dalan 2006), so burned features are also detected with MS survey.

Hearths are sometimes detected because of burning. The main problem with hearths is their small size, making them difficult to distinguish from other small anomalies, noise, and clutter. In some cases, however, a small hearth can be recognized by its context and magnetic properties. For example, if hearths are expected to be located near the center of structures, and the structure's walls or other components are detected, then a small anomaly at the center is more likely to be a hearth than a small anomaly without architectural context. In addition, if a positive magnetic anomaly is also detected in another data set such as GPR, it is more likely to be a hearth or similar feature than anomalies that show up in GPR but not in magnetometry. The size of the hearth and intensity of use are also important factors in their detection. A small,

unprepared hearth can be detected with magnetometry if sampling density and contrast are high enough. If its fill contrasts with the surrounding soils, it could also be detected with GPR using a high sampling density. Larger, more formally prepared hearths, such as those with clay or stone linings or those that are simply larger and more heavily used are somewhat easier to detect. They will still be relatively small features, however, and are not likely to be detected and recognized with resistance or conductivity. In some cases hearths can be recognized by the strength of the magnetometry anomaly. There is no known range of values for hearths, but if a portion of them at one site are confirmed by excavation, these can be used to identify a range of values to identify other similar hearths (Bales 2003).

Structures that were burned are much more likely to be detected with geophysical methods, particularly by magnetic methods, than similar structures that did not burn. For electrical methods, the effect of burning is minor but the firing of clay floors and other effects of burning can change porosity and therefore conductivity, thus changing electrical contrasts. A house or other architectural feature that has been burned, however, will almost certainly be identified with magnetometry and MS because the heat from the fire will partially magnetize the materials.

Accumulations. Accumulations are features that were created from the localized concentration of material. Middens, for example, form from the gradual addition of waste at the same location. At a few sites trash middens are very large and are still visible on the surface topographic features. At most sites, however, they have little or no topographic expression but can be spread out over large areas. Often surveys are conducted entirely within the limits of midden deposits, so they are not detected unless the survey extends far enough outside the main occupation or dumping area. Midden strata are often much less compacted than surrounding materials, and can therefore absorb relatively more moisture in wet conditions, but also drain more readily after a rain event. For this reason middens may be visible with resistance and conductivity if they are small and discrete. They are somewhat less likely to be detected with GPR, because they often lack discrete boundaries on all sides. Detection of midden deposits with magnetic methods strongly depends on the magnetic properties of the materials they contain. If a lot of soil and burned material is added, then they will have elevated MS.

5. CHOICE OF INSTRUMENTS

Geophysics is a broad field of study, with applications in mineral and groundwater exploration, utility mapping, and detection of unexploded ordinance, to name a few (Mussett and Khan 2000; Reynolds 1997). Archaeology makes up a tiny fraction of the market for geophysical instruments, so most of them are designed for other purposes, and have to be modified or used in ways not originally intended by the manufacturer in order to collect data suitable for archaeology. Many of the available instruments are simply not suitable for archaeology, due mainly to depth and resolution limitations. Since geophysics has long been used by archaeologists in the UK, there are a few manufacturers there that make instruments specifically designed for archaeology. Otherwise, instruments designed mostly for coarse sampling densities and very large contrasts must be adapted for detecting comparatively low-contrast archaeological features. In this chapter we describe a number of the currently available instruments that are most suitable for archaeology. This list (Table 4) will, of course, quickly become outdated as new instruments become available.

5.1 Electrical Resistance

There are a great variety of resistance instruments on the market, but almost all of them are designed for geological or related fields of study. Though usable, they are not designed for efficient data collection on the scale that is useful for most archaeological sites. In fact, at this point there is only one manufacturer (Geoscan Research) selling resistance instruments designed for archaeological use. Geoscan resistance instruments are designed to collect data with a twin probe array, and offer extended arrays so that multiple data points can be collected with each reposition of the instrument. In addition, the MPX multiplexer allows the programming of a variety of other probe configurations and the option of making measurements at multiple depths. Geoscan resistance instruments, particularly the RM15 with five-probe array and MPX multiplexer, are probably the most efficient, flexible, and well-designed resistance meters available for archaeological surveys today. The systems are roughly comparable in price to gradiometers and GPR systems, and are not designed for portability. They can be transported by car, but for air travel they must be disassembled to fit into boxes small enough to be checked as baggage.

Another resistance meter that was for sale until recently is the TR/CIA. This instrument, designed by the Council for Independent Archaeology (CIA) and manufactured by TR Systems (both based in the UK), was much more affordable than the Geoscan instruments. The TR/CIA provides a simple twin-probe array with a fixed probe spacing of either .5 m or 1 m. It is not capable of multiple depths or other programming, but is otherwise very functional, efficient, and light-weight. Manufacture was halted to comply with new EU regulations restricting the use of certain alloys, which

made production of the TR/CIA no longer feasible (Council for Independent Archaeology 2009). Manufacture may resume in the future.

Table 4. List of Instruments and Manufacturers

Manufacturer	Resistance	Conductivity (EMI)	Magnetic Susceptibility	Ground Penetrating Radar	Magnetometry
Bartington Instruments	-	-	MS2D Searchloop	-	Grad-601(-2) Fluxgate
	-	-	MS2F Probe	-	-
	-	-	MS2H Downhole	-	-
Gem Systems	-	-	-	-	GSM 19 Proton
Geometrics	-	OhmMapper	-	-	G-858 Cesium
	-	-	-	-	G-856 Proton
Geonics	-	EM38(B)	EM38(B)	-	-
	-	EM31	EM31	-	-
	-	EM39 downhole	EM39S downhole	-	-
Geophex	-	GEM-2	GEM-2	-	-
Geophysical Survey Systems, Inc.	-	EM Profiler	EM Profiler	sir-3000	-
Geoscan Research	RM4	-	-	-	FM256 Fluxgate
	RM15	-	-	-	-
Mala Geoscience	-	-	-	RAMAC/X3M	-
Satisgeo	-	-	-	-	PMG-1 Proton
Scintrex	-	-	-		NAVMAG Cesium
	-	-	-	-	ENVI MAG Proton
Sensors & Software	-	-	-	PulseEKKO PRO	-
	-	-	-	Noggin	-
TR Systems	TR/CIA*	-	-	-	-

*currently unavailable, but manufacture may resume.

A third option is to build your own instrument, which consists of a low-frequency electric current source, a voltmeter, and a digital data logger. The construction is not so simple that anyone could do it, but some have built their own, using basic electronic and do-it-yourself skills. Detailed instructions on how to build a resistance system have been reported in popular electronics magazines, most notably Beck (1997a, b). Homemade systems would probably not be as fast or well made as commercially manufactured systems such as the RM15, however.

A problem is encountered if one intends to rent a resistivity meter for an archaeological survey. Neither of the above mentioned manufacturers rents its equipment. At this time if you are not able to build one or borrow it from a friend, then your only option is to buy a Geoscan resistance meter.

5.2 Electrical Conductivity

There are a variety of instruments available for EMI surveys, but only a handful of them are suitable for typical archaeological work. The most common and probably most successful in North American is the EM38, manufactured by Geonics, Ltd (Ontario) (Clay 2006). With a relatively high frequency (fixed at 14.6 kHz), it works quite well for archaeology with a depth penetration of about 1.5 meters or .75 m using two different instrument orientations. Geonics also manufactures the EM31, which has a much lower frequency and greater depth penetration. Though it is not suitable for detecting typical archaeological features, it is very effective at mapping large features, particularly earthworks and associated borrow pits (Dalan 1991). The EM31 operates at a fixed frequency of 9.8 kHz, with a horizontal coplanar skin depth of about 6 m.

There are also a handful of multi-frequency fixed-coil instruments. The GEM-2 (Geophex Ltd.) can operate in a frequency range of 300 Hz to 24 KHz, and claims to map multiple depths at the same time (Won, et al. 1996). This frequency range extends beyond the high frequency EM38 and the lower frequency EM31, and should therefore penetrate a range of depths from tens of centimeters to tens of meters. A similar multifrequency instrument called the EM Profiler has also been recently developed by GSSI (New Hampshire), but it is so new that not many have had a chance to use it. To our knowledge, neither of the multi-frequency instruments mentioned above has produced good results for the kind of archaeological applications confronting archaeologists in the US, and more experimentation is needed. We strongly recommend that prospective users lease one of these to evaluate its performance prior to purchase. All of the instruments discussed here are available for rent directly from the manufacturer or through other companies.

5.3 Magnetic Susceptibility

Two main single-coil magnetic susceptibility (MS) instruments are available for purchase, both from Bartington Instruments (UK). The MS2D, most commonly used in Europe and the UK, uses a large-diameter search loop and penetrates to about .10 m. The MS2F, also used in Europe and the UK, utilizes a probe and penetrates to about .01 m. The former is obviously preferred for its depth penetration, but the probe system is better for uneven ground because both of these sensors require full ground contact. It is difficult to place the search loop of the MS2D correctly where the ground surface is rocky or irregular (e.g., a plowed field) (Clark 1996). These instruments are also useful for taking measurements of exposed soil profiles. There are a handful of single-coil hand-held sensors for rapid field measurements, which are handy for evaluating the walls of excavation units and other exposures. For rapid field assessments of soil samples, Bartington makes the MS2H, which penetrates .025 m. Similarly, the Geofyzika KT-5 Kappameter is a handy field tool that penetrates .02-.03 m (Lecoanet, et al. 1999). These can be used to map trench walls and other exposures (Reynolds 2002).

Dual coil sensors have long been utilized to measure MS for archaeology, including the SH3, CS60, and CS150 sensors used and developed in Europe (but not for sale commercially) (Benech and Marmet 1999; Parchas and Tabbagh 1978; Tabbagh 1986). In the U.S. and abroad the EM38, manufactured by Geonics Ltd. has been used with considerable success. The EM38 measurements are in parts per thousand (ppt, ratio of the primary to secondary magnetic fields), but can be converted to volume MS using a simple equation if desired (McNeill 1986). Depth of penetration for the EM38 (for the in-phase component, or MS) in the vertical magnetic dipole orientation is about 0.5 m, and probably half this when tilted to the horizontal magnetic dipole. The dual-coil method is the most common in North American archaeology (Dalan 2006). Other dual-coil methods include the multifrequency, fixed coil sensors mentioned in section 2.2.2 for measuring conductivity. Little is known about the ability of these instruments, such as the Geophex GEM-2, to accurately measure MS, and limited field studies are not encouraging (Ernenwein 2002). The Geonics EM38 is probably the most economic sensor for surface MS surveys, as it is the fastest and doubles as a conductivity meter. The EM38B model is preferred because it allows conductivity and MS to be collected simultaneously (Clay 2006).

Downhole sensors are also in short supply. Geonics makes a dual-coil downhole sensor, the EM39S. It is limited, however, because it requires a 2-3 inch diameter hole and the vertical resolution is restricted to perhaps .30 m (Dalan 2006). A new downhole sensor, the MS2H, was recently developed by Bartington in conjunction with Dalan (2001). It is much more suited to archaeological applications, with the ability to resolve layers on the order of .02-.04 m, and the sensor is small enough to fit into a one-inch diameter auger hole. There are also a variety of laboratory sensors. One laboratory sensor commonly used is the Bartington MS2B, but many others exist.

5.4 Magnetometry

There are a variety of magnetometers available for archaeological use. Factors to consider include the configuration (gradiometer or total field), type of magnetometer (proton precession, optically pumped, or fluxgate), and cost. Proton precession magnetometers are the slowest of the three, but are also very affordable (Kvamme 2006b; Witten 2006). The Geometrics G-856 proton magnetometer has seen much use in archaeology. Other proton instruments include the Scintrex ENVI MAG, the Gem Systems GSM 19, and the Satisgeo PMG-1. Though these sensors are usually not practical for area surveys, they can be used as base stations while a faster instrument is used as a rover for a total field survey. For example, a Geometrics G-858 cesium vapor magnetometer can be used as a rover, while a Geometrics G-856 proton magnetometer is used for the base station. This is cheaper than using two cesium sensors as a gradiometer. One drawback, however, is that the readings from the rover and base station will not be time-synchronous and the proton measurements will have to be interpolated to match the rover measurements. It works reasonably well, but is sometimes not adequate if there is a magnetic storm during a survey. If possible and affordable, two cesium sensors should be used.

Cesium vapor and other optically pumped magnetometers are the most sensitive of the three types of magnetometers. Magnetic fields can be measured to the nearest .01 nT, whereas it can only be measured to the nearest .1 nT with other instruments (Clark 1996). These instruments are also less prone to drift than fluxgate magnetometers, and do not have to be tuned more than once per project. The Geometrics G-858 cesium magnetometer is often used in archaeology, either as a single rover (using a separate base station), or as a gradiometer. One small problem is that the setup of this instrument is not ideal for archaeological survey, because the sensors are mounted on a long staff (to minimize interference from the data collector that is mounted to the surveyor's midsection). The long staff is quite heavy and prone to bouncing during survey, adding noise to the data. It is strongly recommended that this system be reconfigured so that the horizontal boom is held vertically by one person, while a second person carries the data logger as far away as the cables permit (Figure 8a). This greatly improves the stability of the sensors, and allows a large vertical separation for greater sensitivity (see section 2.2.4). Data collected in this way by the senior author at Tiwanaku (Bolivia) was so smooth and stable that almost no data processing was required beyond assembling the transects into a map, and correcting timing errors. Scintrex (Ontario) makes another cesium-vapor magnetometer called the NAVMAG. It is meant to be mounted on a backpack, but could probably be modified for archaeology similar to the Geometrics G-858.

Fluxgate magnetometers are the most commonly used type of magnetometer for archaeology, especially in Great Britain. This is mainly because there are two fluxgate magnetometers, both manufactured there, that are specifically designed for archaeology. This is in stark contrast to other magnetometers and most geophysical instruments in general, which are designed for geology and other less related applications. Two fluxgate sensors are available: the Geoscan FM256 and the Bartington Grad601. Both instruments are excellent for archeological work, and both offer dual-gradiometer configurations. Using the dual Geoscan instruments, two gradiometers are mounted on a light-weight frame and effectively collect two lines of data at one time. This permits either a doubling of data density or rate of survey. The data are downloaded as separate data sets, but integrated quite easily and then processed together. The Bartington fluxgate gradiometer can also be configured with two sensors, but the difference is that all the data are logged into one data collector, so they are assembled into one data file at once. While the Geoscan approach requires one more step, it allows the complete separation and independent use of the two gradiometers. Use of a single instrument might be desirable, for example, in wooded areas where the dual instrument frame could not easily be carried between trees. With the Bartington dual system, the two gradiometers are permanently linked. The dual Grad601 (Bartington) may be preferred, however, because it is considerably less expensive than the FM256 dual gradiometer system. It is also much easier to tune, as the process is largely automated, takes only a few minutes, and is only necessary once per day.

One problem encountered when choosing a magnetometer for an archeological survey is instrument availability. Both fluxgate systems discussed here are not commercially available for lease. If a project is to be conducted using rented equipment,

the choices are limited to cesium and proton magnetometers, most notably those mentioned above.

5.5 Ground Penetrating Radar

The two most commonly used GPR systems for archaeological survey seem to be the SIR-3000 (and its predecessors), manufactured by Geophysical Survey Systems Inc. (New Hampshire), and the Pulse-EKKO PRO (and its predecessors) manufactured by Sensors and Software (Ontario). Both of these systems are excellent choices for archaeological work. The GSSI SIR-3000 is very light-weight and can be easily operated by one person in the field (though a second person is handy to help set up transects). A variety of antennas can be used with it, most notably the 270 MHz and 400 MHz models. The Pulse-EKKO system can be used with companion antennas of 200, 250 and 500 MHz, for similar results. It is also light-weight and has several different options for configuration, including some antennas that are separable for velocity tests such as common-midpoint (CMP). Sensors and Software also makes a “Noggin,” which is a very simplified GPR system. Operation complexity is reduced by fixing many of the parameters that are manually set with a more professional system, thus making it less flexible but easier for the beginner. Another system called a RAMAC, manufactured by Mala Geoscience (Sweden and USA), is also used in archaeology and offers similar functionality as the GSSI and S&S systems. It offers 250 and 500 MHz antennas and a light-weight operating system. All of these systems are available for lease.

6. DESIGNING A FIELD STRATEGY

This chapter focuses on the factors to consider when planning a field strategy. Once it has been determined that a site is a good candidate for geophysical investigation, and appropriate geophysical methods and instruments have been selected, the next step is to plan the survey. The size, shape, orientation, and exact location of the survey grid must be determined and implemented in the field, and decisions must be made about the sampling density and method of collecting data. Sometimes the area must be prepared for survey, which may include removing vegetation and clearing the area of metal debris.

6.1 Survey location and size

Project goals and expectations based on previous investigations often help one develop a sampling strategy to guide the geophysical work. In many regions, for example, subsurface features are likely to be correlated with areas of higher artifact density or topographic rises. In general, it is best to begin geophysical surveys in more promising and better understood areas as a baseline before moving toward the lesser known. When a site is very large, and there are generally no clues as to where subsurface features are most likely to be located, choose a readily accessible portion of the site that is not in need of much preparation work (vegetation removal, etc). After collecting a day's or half-day's worth of data, hopefully the results will help you decide which way to progress. At large sites it is often best to select a few discrete locations for test surveys. If possible, keep them on the same grid system, so that they will eventually be connected if the survey is expanded. (Note, however, that unlike most softwares, *ArchaeoMapper* treats surveys like GIS data layers, and does not require consistency in tile or grid size and orientation). Large continuous areas are almost always more informative than small, discrete patches (Kvamme 2003). In some cases there are known archaeological features because of surface evidence (vegetation or topographic markings) or from excavations.

Once it has been determined that the available instruments and selected survey strategy are detecting anomalies that appear to be consistent with archaeological features, a ground-truthing strategy should be considered to aid in directing the progress of geophysical survey. This is particularly important when geophysical anomalies do not take on recognizable patterns that are obviously cultural in origin. Most anomalies can not simply be assumed to be features until some ground truthing has been done. This independent evaluation of the anomalies can sometimes be accomplished using a small diameter soil probe, by correlation of anomaly location and other characteristics with previous excavations at the same site, through reference to historic maps or aerial photographs (particularly for relatively recent sites), through correlations with surface topography or other visual evidence, shovel test pits, or formal excavations (Hargrave 2006). Surveys are sometimes conducted by geophysical

practitioners who are not experienced field archaeologists. In this case, ground truthing often occurs after the survey is complete. Whenever possible, however, it is highly desirable for geophysicists to have some ground truthing information while the survey is underway. This can help ensure that too much time is not devoted to areas where anomalies are, in fact, not associated with archaeological features.

Geophysical surveys can vary greatly in size. Ideally, a survey should extend a little beyond the site limits. Minimally, however, one must ensure that the area surveyed is large enough that features can be recognized based on pattern recognition (Kvamme 2003). There are several scales to consider. Small features can be detected with small surveys, perhaps 15 x 15 meters or even smaller in special cases. Such small area samples may, however, make it very difficult to interpret distributional patterns. Much larger surveys have the benefit of revealing not only individual features and feature clusters, but entire settlements. At this "landscape" scale, (Kvamme 2003), the spatial layout of complete sites can be documented, and entire settlements (or, in many cases, settlement palimpsests) can be investigated. This landscape perspective is one of the great strengths of remote sensing, since the vast majority of archaeological sites are investigated and interpreted based on the excavation of very small areas. The combination of large-area geophysical surveys and carefully targeted, small-scale excavations can provide a great deal of information about site character, layout, and condition at relatively low cost. In many cases, the geophysical data can be used as primary data from which to make archaeological interpretations, and make it possible to ask questions about spatial behavior that could not be addressed or even formulated using excavation data alone (Kvamme 2003). Geophysical data usually do not, of course, provide information about feature chronology, the likely presence of multiple (possibly unrelated) occupations, and so forth. Geophysics is thus a valuable tool for archaeology, but it does not obviate traditional archaeological methods.

6.2 Setting up a grid

The term "grid" can be confusing sometimes because it is used in many different ways. Archaeologists use the term to refer to a simple coordinate system that divides the site into smaller units. In geophysics, however, the term is often (mis)used to mean an individual unit within the overall grid system. To avoid confusion we use the word "grid" here in the traditional sense, and describe the individual geophysical survey units in a grid as "tiles." Note that *ArchaeoMapper* refers to a group of tiles as a "survey".

There are a variety of ways to set up a grid for geophysical survey. For small areas, tape measures can be used without the help of a transit or similar device. Right-angles for tile corners can be closely approximated using the Pythagorean Theorem. For example, to set up a 20 x 20 m grid, one tape is used to define the first tile's (and the overall grid's) orientation. In this example, we will assume the first tape is oriented north-south. The zero point of a second tape is placed at the zero point of the first tape and extended 20 meters to the east. The zero point of a third tape is placed at the 20-m point on the first tape, and extended 28.28 m to the southeast to intersect the second tape at its 20-m point. The process is repeated to establish the tile's fourth corner (here

the hypotenuse tape is extended to the northeast from the zero point on the first tape), and to set-in additional tiles. This method works well for small grids, but as the size of the grid increases, the error gets progressively worse as new grid points are set using previous ones. Even if the original grid corner (datum) is used for all tiles, tape measures will introduce error as they stretch and bend over longer distances. Grids set up with only tape measures often have lines that are not straight and eventually, some tiles may have substantial errors. If this approach must be used, it is important to record the GPS locations of the tile corners. When relocating a point on the ground to investigate an anomaly, one should tape distances from the corner of that particular tile where survey began.

A dumpy level or an optical square can be used to sight in straight lines and right angles, but taped distances will still be erroneous the farther the grid is extended from the starting point (Gaffney and Gater 2003). A much more accurate and precise way to set up a grid is to use a total station or survey-grade GPS. The importance of accurately setting up a grid cannot be stressed enough. If the grid has internal error, or if it cannot be accurately located on the ground in relation to a base map, then the value of the geophysical survey is greatly diminished. Errors in the grid are, of course, more troublesome at sites where the focus is on relatively small features such as pits. Here relatively small grid errors can lead to ground truthing excavations being mislocated, thereby leading to spurious results. Copious notes should also be taken so that the grid can be relocated in the future.

The orientation of a grid with respect to architectural or other linear features is extremely important. Several problems can occur if data are collected along lines that are parallel to walls or other linear features (e.g., ditches, fences, roads). First, a narrow linear feature could be entirely missed if it falls between relatively widely spaced data collection traverses. Or, if the linear feature is detected, anomalous readings may occur along the entire length of one or more lines of data (traverses). When anomalous readings are confined to the line-direction (rather than across lines), they can be easily mistaken for instrument malfunction or interference from outside sources such as radio transmissions. In addition, anomalies that parallel data collection lines will often be entirely removed by a de-striping filter, a commonly used processing algorithm for many types of geophysical data. It is therefore important to choose a grid orientation that is at least 20 degrees offset from the dominant trend in architecture. This sometimes means establishing a different grid than is already in place for excavations, but it is an important and worthwhile step. Where possible it is beneficial to set up the grid close to 45 degrees offset from the architecture (or linear features of interest). Other factors, such as the orientation of above ground obstacles (fences, buildings), should also be considered when choosing a grid orientation. Inside the boundaries of a fence, for example, it is best to orient the grid parallel to the fence as long as this is not also parallel to the architecture.

6.3 Tile size

Tile size is often a difficult decision to make, and there are many factors to consider. Using very small tiles (e.g., 10 x 10 m) over a large area will result in an unnecessarily large number of data files. Each tile must, of course, be established using tapes or a total station, so using small tiles would increase the amount of time spent setting up and preparing for each survey. If tiles are too large (40 x 40 or larger), it will take too long to survey each one and the surveyor will probably need to take breaks before a tile is complete. Stopping a survey before a tile is completed introduces many problems. First, most instruments drift over time, even when data are not being collected. When survey is resumed after a break, the readings of the new line will not match well with the line of data collected before the break, so an edge-discontinuity is created (even if the instrument is re-tuned). While there are always edge-discontinuities *between* tiles, they are less problematic to deal with in data processing compared to edge-discontinuities that are *inside* tiles. With large tiles it is inevitable that sometimes a survey will have to be stopped before it is completed. Data collection has to stop at the end of the day and when batteries are drained, so it is best to use a tile size that is both large enough to keep the number of data files manageable, while also small enough that a tile can be finished in under an hour. Note that *Archaeomapper* is designed to process edge discontinuities that occur between and within tile boundaries with ease, and allows tiles of different sizes and data densities in the same survey.

Another problem with large tiles is with the management of the “walking rope” or tape measure that guides the surveyor along each traverse and is moved as survey progresses. Spatial control is generally maintained by moving an incremented rope that is oriented perpendicular to the tile’s two baselines. When two such perpendicular ropes are used simultaneously in a rapidly progressing magnetic survey, field assistants often flip one rope over the surveyor’s head while he or she is collecting data along the second rope. Long ropes are difficult to move in this manner. Situations also occur where the surveyor has only one field assistant and so must move the walking rope, often while holding a magnetometer in one hand. Here too, moving a long walking rope is difficult. Some equipment manufacturers now offer GPS units that could, at least in concept, obviate the use of survey ropes as a means of spatial control. However, current (and very effective) data processing methods that remove stripes, drift, and heading errors rely on the fact that data are collected line by line. Additionally, use of GPS might result in an uneven distribution of data values, and this could diminish the likelihood of detecting the small, low-contrast features that are common at North American prehistoric sites. Despite these problems, GPS controlled surveys are becoming more common, and these issues might be overcome in the near future. Small tiles are also easier when there are other things going on during the survey that need periodic attention, such as talking to the public, helping with other parts of the field effort, or attending to a GPS unit or battery charger. Finally, smaller tiles make it easier to fit a survey into oddly-shaped or confined spaces.

Another factor to consider with tile size is uniformity. To simplify data collection some instruments only allow tiles to be of a certain size, often in 5 m increments. A widely used standard tile size, particularly for resistivity and magnetometry, is 20 x 20 m. The most commonly used software packages for magnetometry and resistivity (Geoplot and ArchaeoSurveyor) also follow this convention and require that all tiles be the same size in order to be displayed and processed together, which simplifies programming. *ArchaeoMapper* allows different sized tiles to be displayed and mapped together, however. On the other hand the most widely used GPR and EMI instruments and software make no requirements about the size, shape, and uniformity of grid tiles. When using multiple methods at one site it is best to pick one tile size for all instruments. This way, the grid can be set up with markers at every tile corner, and a single set of pre-cut survey ropes can be used for all instruments. A common method in North America is to lay out a grid with markers every 20 meters. If less than two field assistants are available, data for each tile are collected using twelve pre-cut and marked survey ropes. Two ropes are laid down at either end of the tile, and the rest of the ropes are laid down along survey lines at all odd meters (1, 3, 5, and so on up to 19 m). Using this technique, there are no locations in the tile that are more than 1 m away from a survey rope, so distances along each transect can be easily estimated for rapid survey.

The type of rope used is also important. Nylon and polypropylene rope stretch a great deal, and natural-fiber ropes (manila, cotton) shrink when wet and rot over time. A much better choice is fiberglass surveyor's rope, which comes marked with distance units, stretches very little, and holds up well over time. While reel tapes can be used for GPR and resistance surveys, it is essential that ropes used in magnetic surveys be free of metal fittings.

Ground penetrating radar survey is distinctly different from the other methods and it is often better to use larger tiles. Each GPR tile consists of a series of separate reflection profiles, which must be compiled, processed, and then sliced for each tile. If a mosaic of GPR slices is desired, each tile must be processed and sliced individually using most commercially available software (*ArchaeoMapper,* however, was designed in part to improve GPR data processing, and allows many tiles of GPR data to be assembled into a mosaic before creating depth slices). Time required for data processing can therefore be reduced when larger tiles of data are collected. Collecting GPR data using 40 x 40-m tiles is efficient in several ways. The edges line up with the typical 20 x 20 m tile boundaries of other surveys, but there are only one quarter as many tiles to process. Additionally, at half-meter line spacing it is likely that an entire 40 x 40 m tile can be surveyed in 3-4 hours, meaning that two tiles can be collected in a typical 8-hour day. Two 50-meter measuring tapes are used for baselines and a third one as a "walking tape," which is moved along as lines are surveyed. If time is short, 20 x 40 m tiles can be collected. There are many different ways to organize GPR data collection, but we suggest that larger tiles be used to minimize processing time, and that the boundaries are made to match other tile boundaries. Keep in mind, however, that this method requires at least two and preferably three people, and does not leave much time for breaks during the long surveys. A somewhat similar situation with respect to processing time is encountered with EMI, but larger tiles are not recommended because, unlike

GPR, EMI data (both conductivity and MS) are prone to drift. With a sensor that drifts it is better to tune it frequently, such as before each 20 x 20 m tile.

6.4 Data Density

The ability to detect small or low contrast features depends heavily on the data (or sampling) density of the geophysical survey. One factor is the spacing of measurements along each survey traverse. With GPR, the sampling density is very high along traverses (typically 20-100 traces/m), but relatively low between lines (typically .5-1 m). Most other methods suffer from a similar, though less dramatic disparity between high data densities along transects, but rather low data densities in the opposing direction. This is because it takes much more time and effort to increase the number of transects in a survey than it does to take more measurements per meter along each transect. The limiting factor for feature detection and image resolution is therefore the distance between lines. The traditional sampling density for most methods is reported to be one or two samples per square meter, with recent advances in the capacity of data loggers allowing four per square meter and very recently even more (Carr 1982; Gaffney and Gater 2003). These data densities can be achieved using lines spaced 1 m apart, so survey is rather rapid. Gaffney and Gater (2003) suggest that one-meter traverse intervals are still adequate for the majority of surveys; while half-meter (and lesser) intervals are used for research-oriented surveys. That is, however, a UK/European view (where many sites have high-contrast features), and we suggest that the traverse interval should be geared more to the nature of the site and expected features. Data density should be high enough such that the smallest feature to be detected is recorded at least twice and preferably more for reliable detection (Kvamme 2003). This means that if the target feature is one meter in diameter the data density should be at least .5 x .5 m so that it is likely to be recorded more than once and therefore distinguishable from a data spike. At sites with large and/or high contrast features, such as historic sites or high contrast prehistoric sites, sometimes one-meter traverse separation is adequate. Even relatively small features, if they exhibit very high contrast, can be detected with magnetometry and EMI when the instrument passes nearby not directly over the feature. Thus, for magnetometry and MS surveys, transect spacing depends on both feature size and contrast.

Unfortunately, the advantages of high data density surveys are accompanied by higher costs. In practical terms, it takes nearly twice as long to collect data along twice as many traverses, and this obviously increases time in the field and project costs. A balance between meeting the goals of the survey and controlling costs must be found. This sometimes means surveying a smaller area with higher data density rather than a large area at a lower density, or vice versa. When in doubt, we suggest that the interval between measurements be no more than a half meter. Some software packages (including *ArchaeoMapper*) allow one to remove every other line of data in order to assess the impact on anomaly detection. Where this capability exists, it is wise to begin with a higher density survey, and reduce this if anomalies consistent with features are detected using the lower density.

The term data density can sometimes be confused with *image* resolution. Data density refers to the number of data values per square meter collected in the field. During processing, interpolation procedures are often used to cosmetically improve an image by reducing pixel size. Such interpolation is, however, no substitute for an increase in true data density, and it will not aid in the detection of small or low contrast features.

Many instruments are designed to record measurements at regular intervals along each transect. Most magnetometers and EMI instruments emit an audible beep at regular intervals, such as every second, in order to guide the surveyor. The surveyor can then choose how many measurements will be taken between each beep, or can alter the time interval between beeps. When the surveyor walks along and passes a meter mark at every beep, a constant number of readings will be collected per meter, and the readings will be evenly distributed. This requires that the surveyor is able to proceed at a fairly constant pace. If there are many obstacles, readings can be taken manually by pushing a button, although this is difficult in situations where 8 readings per meter must be recorded. Alternatively, some instruments allow the surveyor to keep track of distance continuously by recording a fiducial-mark every meter or so. The meter marks are then used to interpolate, or "rubbersheet", between markers. This is often done with GPR, but an easier way to record GPR data is to use a survey wheel. The wheel attaches to the antenna and works as an odometer, taking an equal number of measurements per meter, and adjusting the rate of data collection as survey pace increases, decreases, and pauses.

6.5 Ground Surface Preparation

While it is ideal for a site to be blanketed in short, smooth grass, most sites are covered in some combination of tall grass, cacti, bushes, and trees. Surveys that involve dragging an instrument along the ground, such as GPR and sometimes EMI, require that the vegetation be cut short enough to allow smooth movement of the instrument across the surface. Magnetometers can be used in taller vegetation because the bottom of the sensor is normally at least .20 m above the ground. One cannot, however, dodge occasional bushes or other obstacles while continuously collecting data since this would introduce many location errors into the data. Resistance surveys require less vegetation clearing, but moving the probe array through dense grass and around bushes can be frustrating, tiring, and slow. The ideal solution is to remove any vegetation that impedes the movement of geophysical equipment. The method of vegetation removal should be carefully considered. A lawn mower can be used to clear grass, but care should be taken not to do this on days when the ground is soft because shallow tire tracks can be detected by most geophysical methods. If bushes are removed, they should be chopped down to ground level but the root system left in place rather than removed because this would create an anomaly on its own.

As discussed previously, metal debris on and near the surface creates a problem for magnetometry survey, and to some extent conductivity. If metal debris is extensive, then magnetometry survey is not worthwhile until the debris is removed. This adds

considerable time and cost to the project, because removing metal entails locating each piece with a metal detector and then usually digging for it with a trowel. This kind of impact might not be acceptable at some (unplowed, cemetery, battlefield) sites. It is a worthwhile effort, however, when magnetometry is the best method for meeting the survey goals.

6.6 Survey Supplies

A variety of field supplies are either required or very helpful for a geophysical survey, particularly for large surveys using multiple instruments. Here we provide a list of basic supplies needed for a survey, but it is not exhaustive.

Tile corner markers. Plastic sections of ½-inch diameter pvc pipe works well to mark tile corners. They can usually be pounded in easily and are readily visible. They can be written on with permanent marker to show the grid coordinates and tile number, or marked with flagging tape that bears this information.

Plastic or wooden stakes. These are best for pinning survey ropes across grid tiles, and can also be used as tile corner markers. Compared to wooden stakes, plastic stakes or ten pegs are easier to work with, last much longer, and are often cheaper.

Flagging tape. This is useful to mark stakes or other tile markers, and other locations.

Plastic Pin flags. Pin flags are useful for marking tile corners, tuning stations, and monitoring stations. Plastic is much preferred over metal for the sake of magnetometry. We advocate that archaeologists never use metal pin flags at sites that may someday be the subject of geophysical survey.

Rubber mallet. A mallet or hammer makes pounding in stakes easier, and one made of rubber is less likely to damage them. Rubber mallets often include some metal, however, so they should be tested before being left within range of a magnetometer.

Tape Measures. Tape measures are needed when laying out a grid unless a total station is available. They can also be used to stretch out along baselines to set up tiles for survey. It is handy to have three tape measures, 30-50 m long each. It is also nice to have one 100-m tape that you can stretch along a series of tiles, or use to measure the hypotenuse when setting-in tiles. If large GPR tiles are being used, tape measures are best for guiding the survey.

Chaining pins. These can be used to secure one end of a tape, allowing one individual to establish a series of tiles. Make sure to remove them prior to magnetometry or EMI surveys!

Survey ropes. Survey ropes are precut sections of rope with meter markers that are highly visible. They are used to lay out a tile for survey. If the typical 20 m tiles are used, then these ropes should be made long enough to lay across the entire 20 m, with some slack at the ends so a loop can be tied. Meter marks can be made visible with brightly colored spray paint, duct tape, or electrical tape. It is also helpful to use different colors to mark increments, such as every five meters, so that distances along the rope can be easily determined. Fiberglass survey tapes, which do not stretch, are available in large rolls from many survey suppliers.

Notebook and pencils. Obviously there is much information to record in the field. Books with grid lines are helpful for sketching the site grid.

Pre-made Forms. For large surveys especially, it is useful to develop a standard form that can be used to record information about each tile. It saves time if the standard-sized tile is already drawn on the form that can be used to sketch in anything on the surface that will affect the interpretation of the data, such as vegetation patterns and the locations of obstacles. If doing resistivity, it is also useful to record the measurements from each tile coner, so that when survey is continued the remote probes can be repositioned to make adjacent tiles match.

Compass. This is especially important for magnetometry, because tuning and set up require that magnetic north be located rather accurately.

Tunings Stands. Fluxgate magnetometers can be tuned standing on the ground as instruction manuals advise, but it is much better to be elevated above the ground. A plastic or some other non-metal stool can be used for this. It is particularly important for dual sensors, because if they are close to the ground they could each find a different zero, resulting in a strong striping pattern in the data. EM instruments, particularly the EM38, also should be elevated high above the ground for tuning. While the instrument can be held this way while standing, it is very tiring and probably not as accurate because it is not held perfectly steady and at the right angle. A collapsible platform can be made out of pvc pipe or some other non-metal material. Use of a bubble level to ensure that the instrument is being held vertically can reduce the time needed to properly tune a Geoscan gradiometer.

Total Station or some other mapping implement. A total station is best, but an optical transit, dumpy level or optical square can be used for small grids.

GPS unit. The geophysical grid should be mapped into real world coordinates if possible, for record keeping and integration with other data in GIS.

Portable Computer. This is necessary to download data, as most instruments do not hold more than a day's worth. It is also important to take a look at data each day to check for errors and see how the methods are working.

Software. The download and processing software for each instrument should be loaded onto the portable computer, but it is also a good idea to have a back-up copy on disk in case the computer fails.

Means to establish a permanent datum. The geophysical data are not worth very much if the grid cannot be relocated on the ground surface in the future. Unless the real-world coordinates of the grid are known (and can be precisely relocated with a GPS), the geophysical grid should be marked with a datum that will last at least long enough to be more accurately documented. A post-hole digger or shovel should be used to dig a hole and fill with cement, with rebar or pvc pipe embedded for visibility. Sometimes the datum should be low to the ground so it will not be removed, damaged, or pose a danger to passing vehicles. Use of rebar is debatable. It is more durable than PVC, and can be relocated with a metal detector, but will cause a large anomaly in future magnetometer surveys. If using rebar, consider temporarily removing it prior to any future magnetometry surveys.

7. ESTIMATING TIME AND COST

The cost of a single geophysical survey is best viewed in terms of the time required in person hours or days. It is not feasible to estimate actual dollar amounts, since labor and indirect rates vary greatly among organizations and individuals. Here we provide estimates of the time needed for each major aspect of a survey, beginning with the team's arrival at the site. These estimates are values that we would use to plan our own surveys, but they are based on our personal experience rather than detailed written records. We do not figure in the costs of leasing or purchasing equipment, since we do not have fully reliable data on prices, and because the relative efficiency of those alternatives depends on the extent to which purchased equipment is actually used. We are aware of some colleagues who use their equipment frequently and effectively, and others who rarely conduct surveys. Note that our estimates for data collection do not include additional time associated with negotiating the learning curve, nor do we account for adverse weather or other happenings that slow down surveys. When creating a budget these unknown factors should be estimated based on the field conditions. A summary of these time estimates is presented in Table 5.

Vegetation clearing. We discussed in section 3.5 the extent to which vegetation must be removed to permit the efficient use of each instrument. Where appropriate, the best approach is to have the site brush-hogged or mowed. Vegetation debris should be removed from the survey area unless it is very sparse. For most surveys, it is important to have a meter or two of cleared area at each end of the data collection traverses to provide space for starting and ending traverses and turning around. For magnetometer and EMI survey it is best to begin walking in advance of the initial data collection point to set a pace and insure consistent instrument height before the first measurement is recorded. Likewise, movement should continue for a step or two after the last measurement is made. This prevents spurious anomalies caused by one's abrupt starting and stopping motions, and is particularly important at magnetically quiet sites. A similar amount of space is needed for turning a GPR antenna around, especially if a survey wheel is attached or a cart is used.

Even if grass and brush is mowed using a tractor, it may be necessary to use large root cutters, a saw, or a chain saw to cut stumps to ground level in order to allow an EMI instrument or GPR antenna to make continuous contact with the ground surface. Short stumps can also be dangerous for the magnetic or conductivity surveyor, who must pay more attention to his or her timing and position than to exactly where they place their feet. Similarly, tree branches should be trimmed high enough that the surveyor will not injure his or her eyes while walking along the traverse.

Where vegetation is dense and mowing is not possible, it can take much longer to clear a site using hand tools than it does to conduct the survey using a single instrument. Thus, in preparing work plans for an in-house crew or a Scope of Work for a geophysical consultant, it is essential to identify in advance who is responsible for

vegetation clearing, and to have a clear understanding of how thorough the clearing needs to be.

Table 5: Estimated time needed for geophysical survey, data processing, interpretation, and report writing.

Activity [1]	8-hour days	
	Geophys. Tech.	Field Assist.
Establishing grid (25, 20x20m tiles)	.5 - 1	.5 - 1
Data collection, 0.5 m traverses:		
Resistance	4-4.5	4-4.5
Magnetometry (single sensor)	2.5-3.5	2.5 -3.5
EMI (using Geonics EM38 or similar)[2]	3 - 3.5	3 – 3.5
GPR	3 - 4	3 - 4
Data processing [3,5]		
Resistance	.5-1	0
Magnetics	.5-1	0
EMI (using Geonics EM38 or similar)	3-3.5	0
GPR	3-4	0
Interpretive maps (overlays, etc.) [4]	1-2	0
Data fusion (total time for all sensors) [5]	1-2	0
Report preparation (text) [4]	1-2	0
Ground truthing recommendations	1-2	0

[1] All estimates pertain to an area of 1 hectare (10,000 m^2). Note that vegetation clearing is not included.

[2] For either conductivity *or* MS. Double if collecting both data sets unless EM38B (or other sensor that allows simultaneous collectiong of MS and conductivity data) is used.

[3] Full processing

[4] Survey area can be increased to several hectares with no additional time needed

[5] Time can be significantly reduced (especially for GPR and EMI) by using *ArchaeoMapper.*

Establishing the grid. Guidance on how best to establish a geophysical survey grid is provided in section 6.2. Most archaeological research and CRM units have access to a total station. Using a total station is definitely the preferred approach because it is far more accurate than using measuring tapes, and the recorded digital data provide the basis for producing a map that shows the relationship of the survey grid to the overall site. Clearing the vegetation before setting in the corners for all tiles is preferable, particularly if the area must be mowed. However, it is important to have a reasonably clear idea of where the outer limits of the survey area will be in order to avoid needless clearing.

In open terrain, two experienced people should be able to set in stakes marking the corners of twenty-five 20 by 20 m tiles (one hectare) in a half day or so. Using a total

station would be somewhat faster and far more accurate. The presence of trees and other obstacles would add additional time and further diminish the accuracy of using tape measures as a primary means of establishing the grid. Additional time is often needed to decide where to place the grid and which direction it should be oriented.

Data collection: Resistance survey using a Geoscan RM15, the "industry standard" for archaeology, is most efficiently done by a two person crew. One individual moves the instrument along the traverses while the second manages the cable that connects the instrument and the "remote" probes. This cable easily becomes tangled in undergrowth, corn stalks, etc. In really dense undergrowth it can be useful to have two individuals to manage the cable, but in most cases this would not be necessary or cost effective.

For many resistance surveys, it is efficient to configure the instrument with 3 mobile probes in a simple linear array that Geoscan calls "parallel twin". When the mobile probes are spaced at .50 m, the two side-by side readings that are collected nearly simultaneously will cover the full width of a one-m wide traverse. Moving the instrument in .5-m steps along the traverses results in 4 readings per m^2, a good density for resistance survey in most cases. This data density should permit the detection of large and relatively high contrast pits, house basins, and (under favorable conditions) graves. Resistance survey is probably the most tiring and tedious of the methods discussed here, and it is typical to average about one 20 x 20 m tile per hour (when collecting four samples per meter). Allowing for short breaks, instrument setup and break-down, it is common to complete about six such tiles (2,400 m^2) per normal work day. Reducing data density to two values per square meter (i.e., taking readings at one m intervals along the traverse) can increase the number of tiles per day to 12. This would not be advisable, however, unless one was focused only on the detection of large, fairly high contrast features (e.g, house basins, historic architecture other than isolated piers, plowed down mounds, abandoned roads or paths).

Gradiometer surveys are the fastest of the geophysical techniques used in archaeology. As explained previously, the primary factor in the time required to complete a given tile is the spacing between traverses. Under favorable conditions (reasonably large and high contrast features), or where large area coverage is a priority, traverses spaced at 1 m intervals can be cost-effective. Using 20 x 20 m tiles (a common size among those who use Geoscan and Bartington gradiometers) with 1 meter between traverses, at least 20 tiles can be surveyed in a normal work day. This assumes a team consisting of one surveyor and two field assistants to move the ropes. A surveyor and only one assistant can be effective in open terrain, but this is more tiresome and slower because the surveyor has to assist in the movement of ropes (a cumbersome task while holding the instrument in one hand). This rate of coverage includes several retuning sessions (10-15 minutes each) and one data download session (typically done during a lunch break). Recently manufactured or upgraded gradiometers have enough memory to permit surveying all day without the need to download data. This is, however, generally not advisable, as it only takes 20 or 30 minutes (including a retuning) to check

data quality. This is a good way to gage the success of the survey and can help determine which direction to expand survey.

Reducing the distance between traverses to .5 m will essentially halve the number of tiles that can be covered in one day. This greater data density is worthwhile, however, if features are predicted to be small and or low-contrast, or if survey goals call for optimizing image resolution. Using a dual gradiometer (two instruments operated simultaneously) is highly efficient because it allows one to double the data density or the area that can be surveyed per unit time. Advantages and limitations of two widely used brands (Geoscan and Bartington) are discussed in Chapter 5.

Conductivity and MS surveys can be conducted using an EM38 instrument at a rate comparable to most magnetometers. However, instrument drift is likely to be more of a problem, and slightly more time may be required for tuning. Battery life is also more problematic with this instrument, depending on which data logger is used. While the Geoscan and Bartington magnetometers last more than 8 hours, a spare battery for some EM38 data loggers is needed for a full day of survey. The EM38 also uses a 9-volt battery inside the instrument that needs to be replaced about once every 5-7 days during a survey. Due to the additional time needed for tuning the EM38, we estimate that about eight 20 x 20 m tiles can be surveyed per day. If the EM38B sensor is used conductivity and MS can be collected simultaneously and therefore survey time per data type is halved.

Recent developments in GPR, notably the wide availability of carts and survey wheels, have improved the rate of survey coverage. An experienced team of two can now expect to complete the equivalent of two 40 by 40-m tiles in favorable terrain in one day. This assumes that traverses are spaced at .5 m. Battery power varies considerably between brands and models, but often two or three fully charged batteries are needed per day. It takes a day or two for a new surveyor to get used to survey methodologies, including how to hold the instrument and keep track of which lines have already been surveyed. The GPR learning curve is steeper because there are many more parameters to adjust during setup and considerable experience in needed to judge how a survey is going based on reflection profiles visible during data collection.

Data processing. There is a greater range of variation in the time required for data processing than in data collection. One major factor is software. A few software programs have optimized data download and processing for archaeological work, but others are much less streamlined. For magnetic and resistance data (barring any major mistakes made during data collection), one can easily produce draft-quality maps in the field with less than 15 minutes of data processing using Geoplot or ArchaeoSurveyor. GPR slice maps can be created and displayed side by side in less than an hour, though data download can require up to 30 minutes due to the large file sizes. EMI data are somewhat more difficult to download and assemble into tiles and mosaics, so preliminary results are often not available during the field day. However, using *ArchaeoMapper* should make it possible to general draft-quality EMI maps about 30 minutes. In general, magnetometry and resistance maps can often be quickly and easily assembled and viewed almost immediately in the field while GPR and EMI are usually

not viewed until the end of the work day or sometimes after the entire dataset has been collected. Preliminary resistance and magnetometer images made in the field are adequate to evaluate data quality and to make decisions about which areas to survey next. *ArchaeoMapper* addresses the software problem (i.e., the need to use several different software packages) by allowing most brands and types of geophysical data to be directly loaded and assembled in one software environment, including resistance, magnetometry, EMI and GPR. In addition, once data are loaded into *ArchaeoMapper* they do not need to be exported to other programs for simple tasks such as overlaying with one another and with other datasets, and data fusion.

A considerable amount of additional time (but rarely more than a few hours) can be spent in the lab, trying to optimize the interpretability and cosmetic appearance of resistance and magnetic data by experimenting with alternative thresholds, processing sequences, and so forth. Preparing maps for publication or submission to a client is more time consuming. Additional steps typically include importing data processed in specialized software (e.g., ArchaeoSurveyor, Geoplot) into Surfer, a GIS, or other software designed for graphic display (*ArchaeoMapper* eliminates the need for most of these steps). Often it is desirable to import a data layer that includes the outlines of excavation units, excavated features, roads, trees, and other things that will help interpret the geophysical data. The layer containing these outlines is typically overlain atop the geophysical data, labels are added, etc. An experienced practitioner can often produce all such maps for a straight-forward, modest sized (ca. one hectare) magnetic or resistance survey in one work day. Much additional time can be devoted, however, to efforts to understand variation in geophysical anomalies based on excavation data such as the artifact contents, size, and shape of excavated features. Categorizing anomalies in preparation for ground truthing excavations can also be time consuming, depending on the number of anomalies, the criteria to be used, and so forth.

Resistance surveys (assuming a Geoscan or TR/CIA instrument is used) often require the least amount of processing. Unless a great deal of careful edge-matching is needed to remove or reduce the effects of moisture differences during data collection, a draft map can generally be produced in the field in less than 15 minutes. Often the only processing steps needed are an examination of the raw data and its descriptive statistics, clipping to remove outliers, despiking, possibly high-pass filtering, and perhaps interpolating or smoothing. A brief explanation of data processing is given in the next section, and detailed explanations are provided in the *ArchaeoMapper* user's manual and other software manuals.

Magnetic data collected with a Geoscan or Bartington fluxgate gradiometer can also be processed fairly quickly (other instruments not streamlined for archaeology, such as the Geometrics G-858, take longer and are more comparable to EMI survey discussed below). Standard processing steps include inspection of the raw data and descriptive statistics, clipping and despiking to remove or reduce the impact of isolated strong values, removal of striping, interpolation to achieve square pixels, and often a low pass filter to enhance the potential for discerning anomalies associated with relatively small features. In some cases, particularly when dual-sensors are used or if there are numerous high amplitude anomalies, stripe removal can be more time consuming. The

removal of periodic defects associated with the surveyor's stride also adds a few extra steps but generally not a great deal of time. Selecting magnetic anomalies for ground truthing can be time consuming because they are numerous in many surveys, and equifinality is particularly troubling. Magnetic data are also relatively difficult to interpret because there is no simple relationship between the size of a strong anomaly and the dimensions of the associated object.

Processing conductivity and GPR data is much more time-consuming than for magnetics or resistance. GPR data are qualitatively different in terms of their 3-dimensional character. In fact, the excessive amount of time required to properly process GPR and EMI data and then integrate it with other datasets was one of several reasons for developing *ArchaeoMapper*. Some of the particularly time consuming processing steps for GPR data include position corrections, velocity calculation, selective gaining and three dimensional edge-matching between tiles (Ernenwein and Kvamme 2008). For experienced practitioners aiming to produce the highest quality results, GPR data processing can require dramatically more time than resistance or magnetic processing. It should be noted, however, that GPR data can be processed more quickly with acceptable results using only the most basic processing routines and if surveys do not involve multiple survey tiles that require edge-matching.

Interpretation of GPR data is also generally more time-consuming. The three dimensional nature of GPR data allows countless ways to process, visualize and interpret the data. Slice maps and three dimensional translucent renderings aid in interpretation, and individual reflection profiles offer unique perspectives on anomalies and surrounding stratigraphic layers. The process of creating time slices can also be time consuming because you can experiment with different slice thicknesses and ways of mapping the amplitudes. In some cases very thin slices are the only way to visualize anomalies representing archaeological features, while at other times thick slices are required to capture features that occur at multiple depths. Time slices are often the best way to interpret GPR data, and can be directly compared to other geophysical data layers, but more can be learned by looking at anomalies in profile. Since a GPR data set can produce anywhere from one to ten meaningful times slices, interpretation time can easily escalate as more slices are used. Estimating the time required for GPR processing is therefore very difficult. We recommend that at least one person day should be allowed to process and interpret GPR data resulting from a one-day survey of two 40 by 40-m tiles (3,200 m^2). This assumes that the site has a single component. For multiple components there is the potential to create slice maps showing the different cultural layers, which could double the time needed to interpret the data. For complex or multicomponent sites two days might be needed for the same sized data set (3,200 m^2).

Conductivity and MS data collected using an EM38 are also relatively time consuming to process, although the time requirements are substantially less than for GPR. One problem originates with a data logging system and processing software that are not optimized for archaeological survey. Like GPR, each line needs to be edited by correcting errors in distance markers or deleting extra measurements at the end of lines. This can be done with the companion EM38dat software, and then the data can be exported to a spreadsheet program. Next, they should be gridded into a uniform grid,

which can be done using nearest neighbor or some other interpolation in Surfer or another raster program. It is at this point that the data are in a format comparable to the raw data downloaded from Geoscan or Bartington instruments (x, y, z data), and they can be imported into software for processing. *ArchaeoMapper*, however, allows direct import of EM38 files, which should cut data processing time in half for this type of data. Instrument drift is a common problem with the EM38 for both conductivity and MS data, with substantial time required to identify and correct these trends. We estimate that about one day of processing is needed per data type (conductivity and MS) for every one day of data collection. If using *Archaeomapper*, however, EMI processing is much more streamlined and can be done without importing or exporting to other software packages, thus reducing the amount of time needed to process the data by about half.

Report preparation. Estimates for data collection and data processing provided above do not include the time required to write a narrative report. The specificity of reports on geophysical surveys is highly variable. Because many archaeologists have no first-hand familiarity with the various techniques, we believe it is important to produce some written report of each survey. In addition to a discussion of the background material (reason for the survey, site location and characteristics), even the most minimal report should specify field methods (grid size and location, data density, key instrument settings, site characteristics that may affect data quality), specification of the software and routines used to process the data, maps showing project results, a discussion of the types of anomalies detected, and recommendations for ground truthing. It is generally acceptable and efficient to use previously written “boiler plate” discussions of how the instruments work, but these should be adapted to each survey. A minimal report with all of these sections, suitable for inclusion in a larger document, can generally be produced in one to two work days.

8. WHAT TO EXPECT

There is perhaps no better way to learn how to use geophysics effectively than to conduct numerous surveys at diverse sites. Nevertheless, some users and most prospective survey sponsors will want to avoid "wasting" time and money by conducting surveys using instruments or field methods that are inappropriate for a particular site (Hargrave 2007). We have noted previously that one of the realities of archaeological geophysics is that a survey's outcome cannot be predicted with great reliability, it can only be estimated. This is because so many of the interacting variables that affect a sensor's performance vary through time (i.e., seasonally), between—and even within—sites. Unfortunately, this variation precludes a formulaic approach to predicting survey success. Analysis of soil and rock samples in advance of fieldwork can aid in predicting success for some geophysical methods. Heating soil samples, for example, can provide an idea of a site's potential to include features that are detectable with magnetic methods (Clark 1996). Simple field tests can determine if rocks present at the site are highly magnetic and thus likely to represent troublesome clutter. Other soil tests, such as grain size and clay mineralogy can be used to predict the efficacy of electrical survey methods, but this is complicated by fluctuations in moisture that cannot be reliably predicted. For GPR, it would be useful to know something in advance about the mineralogy of the site's clays because highly conductive clays could severely limit depth penetration. Moisture is still the dominant factor, however, and it is often difficult to predict moisture conditions at the time of actual survey. Whenever possible, it is better to simply use GPR equipment to test a small area for survey efficacy (Conyers 2004).

One of the important factors in survey success that cannot be measured is the nature of archaeological deposits. Features can vary in contrast to such a degree that it is impossible to predict how easily they will be detected. One response to this uncertainty is to carefully select only the most promising sites for geophysical surveys so that you will reduce the risk of unfavorable results (Hargrave 2007). This is probably wise in situations where the survey sponsor has little or no previous experience with geophysics, and no time or inclination to become familiar with the issues, or where the social, management, or public relations consequences of an unsuccessful survey are significant. Another school of thought suggests that, since you cannot truly predict which methods will work, you should simply try them all. This is good advice for those determined to become proficient surveyors, but is not practical in most CRM situations, where time and funds are almost always limited. A third approach is to identify a reliable geophysical consultant, provide him or her with as much information as possible about the nature of the site (a good consultant will request such information), and follow their advice concerning sensor selection, data density, and so forth. This can be an effective way to improve one's own skills if the consultant is willing to let the sponsor assist in the fieldwork. Keep in mind, however, that the consultant will have budgeted his or her time on site, and should not have to bear the costs of training a novice unless that was clearly understood by both parties.

One problem often encountered by geophysical consultants is that clients and those unaccustomed to geophysical methods tend to envision the results of a survey much like an X-ray. Even experienced archaeologists who have not previously worked with a geophysicist may not consider the effects of formation processes on the "geophysical record". At many sites, geophysical anomalies resemble a series of amorphous "blobs" that do not provide a clear indication of subsurface deposits. It is the job of the geophysical specialist to first process the data so that it can be more easily understood, and to make interpretations based on his or her knowledge and practical experience. When it is not obvious to the non-specialist which of the anomalies are most likely to be associated with archaeological features, the geophysical specialist can simply point them out using arrows or circles drawn in a graphics software, or by digitizing lines and polygons that show the anomalies' actual dimensions. If multiple methods are used they can be overlaid or fused together using a variety of techniques that allow the simultaneous visualization of several layers at one time (Kvamme 2006a; Kvamme, et al. 2006).

Anomalies can be categorized and prioritized for ground-truthing based on a number of relevant criteria, including their size, shape (circular, linear, or irregular) and amplitude (data value) range (for example: $< -2\sigma$, $2\text{-}3\sigma$, and $>3\sigma$). Additional criteria for categorizing anomalies include discreteness, sign (positive or negative), location relative to other anomalies or site features, and detection by multiple sensors (Hargrave 2006). Alternatively, some types of features can be identified in geophysical data based on knowledge of their physical properties relative to surrounding matrices. Prehistoric hearths, for example, might be predicted where both magnetometry readings and GPR reflection magnitudes are moderately high. Representative examples of each anomaly category can be tested by excavation with the aim of identifying which categories represent cultural features and which ones are the products of non-cultural action such as bioturbation or recent disturbances. In some cases test excavations may show strong correlations between anomaly categories and feature types, allowing those results to be extrapolated to other, untested examples. Keep in mind, however, that diverse subsurface phenomenon (archaeological features, tree roots, rodent burrows, rocks, small bits of metal, etc.) often create similar geophysical anomalies. Collection of high quality data, thoughtful categorization of anomalies, and ground truthing of a representative sample of anomalies can yield a great deal of otherwise unavailable information about a site, but inferences about individual, uninvestigated anomalies are still prone to error.

We cannot emphasize enough that geophysical data always show *something*, whether it is archaeological features, rodent activity, or the effects of modern agriculture or construction. In fact, geophysical data often contain indications of all of these phenomena and much more. It is useful to consider geophysical data as a composite of the following: geology, archaeology, changes in temperature moisture over the course of a survey, topography, and erroneous measurements made by the instrument and user. With experience in data processing, a fair amount of the unwanted variation (the non-archaeological components) can be removed or muted, emphasizing the archaeological component of the data. First, errors in measurement such as data

spikes or accidental jerks of the instrument are very high frequency and are usually apparent as discrete spikes (isolated extreme values) in a data set. These can be removed with a low-pass or de-spike filter. Second, geological and other variations (topography, moisture) usually occur on a broad scale, such as a gradual change across a site from fine to coarse-grained sediments. A high-pass filter can remove these broad trends. Since most archaeological features are neither very high nor low frequency, they remain in the data set (if they were there in the first place) after this kind of filtering and can sometimes be identified by their size, shape, and distribution. A problem occurs, however, when some non-archaeological disturbances, such as rodent holes, pot holes, tree-throws, and the like create anomalies of similar size and shape as archaeological features. These constitute clutter, and are easily mistaken for archaeological features. If anomalies arising from cultural features can be differentiated from clutter (based on size, shape, geophysical signatures, discreteness, location, etc.), the situation is much more favorable than if anomalies arising from cultural and noncultural phenomena have the same expression in geophysical data.

A common misconception among archaeologists with little previous experience in using geophysics is the expectation that archaeological "ground truthing" excavations should *always* be viewed as the ultimate truth about geophysical anomalies. Several possibilities need to be recognized. First, it is not too unusual to find that some archaeological features are simply not detectable with geophysics, despite their obvious appearance in excavations (e.g. see Ernenwein 2008). This does not occur commonly enough to diminish the usefulness of geophysics, but it is a possibility that must be recognized. Second, geophysical maps occasionally include anomalies whose distinctive size and shape indicate that a feature is almost certainly present yet no evidence for the source of the anomaly can be found during excavation (Figure 18). The cause of this dilemma is that human eyes and hands detect variations in color and texture, but not in magnetic or electrical properties. Some features may have a strong visual contrast with their surroundings, but no electrical or magnetic contrast that can be detected with a geophysical instrument. Likewise, some features have electrical or magnetic contrasts, but are simply not visible to the human eye. Such occurrences can be a point of contention among geophysicists and archaeologists, largely because traditional, excavation-based archaeology forms the foundation of our discipline. If a feature is clearly present based on geophysical data, but cannot be found in the ground with a trowel, then should it be considered a "real" archaeological feature? It is, of course, a feature in the sense that it represents the remains of past cultural activity, but it is more difficult to document and study in the traditional way. This problem will have to be addressed as geophysical methods become more widely used. Again, such occurrences are not common enough to offset the many advantages that geophysics can offer the archaeologist. Ground truthing will almost always enhance the information content and management value of a geophysical survey (Hargrave 2006), even if it does not resolve all questions about the archaeological sources of all the investigated geophysical anomalies.

To summarize, properly collected geophysical data provide a map of the electrical and magnetic contrasts that were present in the ground at the time of survey. If

archaeological features are present, contrast sufficiently with their immediate surroundings, and are within the size and depth ranges of the instruments used, then they will be detected as geophysical anomalies. Sometimes archaeological features will be obvious in the raw data due to their distinctive size, shape, and distributional patterns, but much of the time they appear as somewhat ambiguous anomalies that might also be associated with natural or recent cultural phenomena. Anomalies associated with archaeological features can often be identified if appropriate field methods and instruments are used, if clutter is not too pervasive, and if effective data processing and interpretation is done. This guidance document provides decision-making support about whether a site is suitable for geophysical survey, which methods and instruments should be used, and how the field survey should be conducted. The *ArchaeoMapper* user's manual provides detailed guidance on how to process and interpret geophysical data for archaeology. *ArchaeoMapper* allows most geophysical data types to be processed in a single software environment with the aid of wizards and batch processing routines. We hope these resources will help DoD and other CRM archaeologists to incorporate geophysical methods into their research and management programs in an effective and productive manner.

9. INTEGRATING GEOPHYSICS INTO A REGIONAL PROGRAM

In this final chapter we offer advice on how resource managers, CRM firms, and academic researchers can integrate geophysics into their overall research and resource management programs. We view successful integration as using geophysics in a cost-effective manner, at sites where conditions will permit it to yield reliable results. Here the key issues are the selection of appropriate primary and secondary instruments, developing and maintaining in-house geophysical expertise, and identifying the proper role for geophysics in the overall program.

9.1 Selecting primary and secondary instruments

To develop an effective in-house geophysical program, one should acquire at least two instruments. A single instrument that is used effectively can certainly strengthen one's program, but the use of multiple instruments will increase the likelihood of detecting features, permit the detection of a broader range of feature types, and will thus make both positive and negative findings more reliable. Generally the primary instrument should be the most effective at the widest range of sites, while the secondary instrument can provide complementary information. Realistically, of course, the primary and secondary roles are reversed for some sites, and sometimes only one technique or neither is successful. Additional instruments are, of course, even more beneficial and could be added to the inventory once the primary and secondary methods have been established and the benefits of using geophysics have been demonstrated.

Prior to selecting a primary and secondary instrument, it is important to take stock of the characteristics that many sites in one's study area have in common. Even within the bounds of a relatively small study area (for example, a military installation, state or national forest, or particular drainage system), there will be a significant range of variation in factors such as soil characteristics (particularly texture and iron oxide content), moisture, vegetation, rock inclusions and near-surface bedrock, post-occupational impacts (plowing, earth moving), clutter associated with recent metallic trash and infrastructure, and the nature of the archaeological record itself. Often, however, sites that pose the most immediate management problems or those that have the greatest research interest are characterized by a more restricted range of variation in key factors.

Tables 2 and 3 in Chapter 4 provide a starting point for selecting primary and secondary instruments. If the "Excellent" entries are summed for all the features described in Table 3, magnetometry and GPR seem to be the most versatile (they have the most "Excellent" entries), followed by resistance, conductivity, and MS. Summing only those features expected for an area of interest could help identify which types of instruments to purchase for a defined region. Note, however, that Table 3 was constructed assuming environmental conditions were favorable for each method, so it

should not be used without considering all the factors discussed in Chapter 4. Table 2 can be used to help select methods that either benefit or have no adverse effects from regionally prevailing environmental conditions. One will probably find that no single sensor is best for every site, but with two sensors at least one of them will be a good choice for most sites. Each method and instrument has advantages and drawbacks in terms of speed, ease of use, depth sensitivity, and other factors. The bottom line, however, is how well the instrument works in the given situation or region.

If local conditions seem to be favorable for most or all types of instruments, it might be best to choose one magnetic (magnetometry and MS) and one electrical (resistance, conductivity, and GPR) sensor so that the two principal types of contrast can be utilized. In fact, the two most commonly used geophysical survey methods in Europe and the UK, magnetometry and resistance, work quite well together. One thing that favors the use of these two techniques is the fact that Geoscan has long manufactured instruments and companion software adapted specifically for archaeology, making them easier to use than GPR and EMI. The development of *ArchaeoMapper* has made it possible to process GPR and EMI data with greater ease, but those instruments are still not streamlined for archaeology and are therefore more time consuming to use.

Case Study 1: Geophysics in Illinois. Much of the junior author's geophysical work occurs at prehistoric and historic sites in central and southern Illinois. Here most sites tend to be located in agricultural fields, allowing one to schedule geophysical surveys to occur when crops do not pose a problem. Moisture varies enough on a seasonal basis that one can usually schedule fieldwork for favorable conditions. The factor that most limits the success of magnetic surveys of prehistoric sites is feature contrast. Many sites in the Mississippi River floodplain and adjacent uplands are characterized by soils that have modest iron oxide content, with the result that there is often minimal magnetic contrast between features and their surroundings. Prehistoric discard practices also contribute to the problem, since late prehistoric house basins, wall trenches, and pits in the American Bottom region (around Cahokia and greater East St. Louis) frequently exhibit modest densities of artifacts and rich organic feature fill is the exception. Sites north of the Ohio River are generally characterized by little or no daub (clay used as wall cladding that was inadvertently fired when the house burned). Daub occurs throughout much of the mid-south and South, and is advantageous because its remanent magnetism makes it readily detectable in magnetic surveys.

Although the subtle magnetic contrast is a limiting factor in Illinois, magnetic survey remains the single most effective technique, particularly for prehistoric and early historic sites. Its rapid rate of coverage allows magnetic surveys to cover large areas. Often only the stronger contrast features are detected, but this is generally enough to guide excavations, identify feature concentrations, and to provide useful information about site layout. The rapid rate of survey and data processing coupled with the reliable detection of many features makes magnetometry the primary method of choice. Resistance represents a good choice for a second technique in this region. Its rate of coverage is much slower, but it offers the potential to detect pit houses, large pit features, plowed down mounds, and other features in situations where there is a great

deal of magnetic clutter, and at sites where iron oxides in the soil are minimal. It is often effective to use resistance within selected portions of a magnetometry survey to better delineate structures that are difficult to map with only the magnetometry data.

Conductivity survey would probably have many of the same advantages as resistance, although the junior author has not had much first-hand experience with that technique. Conventional wisdom suggests that the high clay content found at many sites in Illinois would not be favorable for radar. GPR might still prove useful at some sites, particularly when the soil is very dry, where clay content is low, or where high contrast archaeological features occur at shallow depth. Despite these possibilities, GPR remains a third or fourth choice for this region because magnetometry and resistance together already provide adequate subsurface information. Funds were recently secured for purchase of a GPR system, but it is too early to determine if this will be beneficial since this instrument is still being tested and training continues.

Case Study 2: Geophysics in the American Southwest. It is also useful to consider which instruments would be best for an arid environment such as the American Southwest, where many sites are on public lands that are used for military training and cattle grazing. The senior author's experience in this region and in climatically similar regions around the world lead to different choices for the primary and secondary instruments. The single most effective method for the American Southwest has been GPR. Radar penetrates deeply in many areas of the Southwest because the soils and sediments are so dry. Electrical resistance is often a poor candidate in desert environments because the dry surface prevents current from entering the ground. Magnetometry is also (sometimes) less successful in arid regions because soil is poorly developed. EMI, however, can be successful because it does not require probes to be inserted into the ground. An excellent example of advantages of GPR and EMI in desert environments is the survey at Pueblo Escondido (Fort Bliss, NM), described in Chapter 4. Based on this and other experiences in desert climates, GPR would be a good primary instrument, with EMI as secondary. GPR detects a wide range of features and provides depth information, and EMI can be used for both conductivity and MS, for a total of three independent data sets. An alternative secondary method would be magnetometry because of its ability to detect remanent magnetic fields from burning or features made with igneous rocks.

9.2 Developing and maintaining expertise

Geophysical instruments vary in terms of the amount of practical experience required to consistently collect good quality data. GPR is clearly the most difficult, followed by magnetometry. EMI in theory is quite complex, but using the instrument and getting good quality data are quite easy. The most straightforward method to master both in the field and understanding of the theory is electrical resistance. In terms of data processing, GPR is again the most difficult, followed by conductivity, magnetics, and resistance. Table 6 summarizes the strengths and weaknesses of the four main instrument types.

Table 6. Strengths and limitations of the four main geophysical methods.

	Survey Speed	Ease of Processing	Learning Curve	Data Density	Other Positives	Other Negatives
Magnetometry	rapid	easy	moderate	moderate	dual sensor options	Metal clutter
Resistance	slow	easy	easy	low	least demand for vegetation clearing	Physically demanding
GPR	moderate	complex	steep	high	depth information	
EMI	rapid	slow	moderate	moderate	2 different data sets No probe insertion	drift problems

The best way to learn how to use an instrument is to work on an individual basis with a competent mentor. A good first step is to attend a brief (3 to 5-day) intensive short course, such as the one held each May by the National Park Service. In fact, attending this course would be wise before one decides which instrument to buy, since it would provide an opportunity to discuss with a number of experienced users the applicability of various instruments to one's own study area. Specialized short courses in instrument use are offered by some equipment manufacturers and other specialists. Such courses are a good way to develop a working relationship with the manufacturer (or at least, their sales/training representative). Such a relationship is important because geophysical equipment can be counter-intuitive (in some cases, quirky), and instruction manuals do not cover all situations. Novice users frequently need advice on short notice (e.g., during fieldwork) about instrument configurations, minor repairs, and data processing, and it is a tremendous advantage to be able to call one's mentor.

The least effective and least responsible approach is to attempt to learn geophysics oneself, relying exclusively on the manual, while doing one's first "real" survey. Everyone's initial surveys are likely to include some poor quality data, sub-optimal data processing, and possibly ill-founded interpretations. It is likely to be detrimental to a customer's view of geophysics in general and oneself in particular to try to "learn on the job" without the support of a competent instructor.

9.3 The proper role of geophysics in a research or compliance program

We conclude this guidance document with a brief discussion of how geophysics can best be integrated into research and compliance programs. First, the geophysical techniques discussed here do not provide an efficient means of locating sites. Traditional approaches including pedestrian surface collection and shovel test surveys are reasonably reliable and cost effective. With the exception of magnetometry and EMI (which detect small metal objects), geophysical surveys rarely detect small artifacts, and many archaeological sites consist primarily of artifact scatters.

Where site conditions are favorable, geophysics is generally superior to traditional approaches for evaluating the presence of subsurface features. In many states, National Register of Historic Places (NRHP) eligibility assessments of archaeological sites are based primarily on the excavation of a grid of shovel tests (often at 10 or 15-m intervals), supplemented by a very small number of hand excavated test units. Such

excavations often expose less than 1% of the site area, making it statistically unlikely that one will encounter widely spaced features like hearths, pits, architectural remains, or burials. In contrast, geophysical surveys can allow one to examine entire sites or, at least, very large portions. Properly conducted geophysical surveys can dramatically improve the reliability of NRHP evaluations. Some excavations are, however, virtually always needed to determine the source of anomalies that may be associated with features, recover artifacts and other materials needed to date the site, document the limits of the artifact scatter, and to evaluate stratigraphy and site condition.

Geophysical surveys can be expensive, particularly if one includes instrument costs, in-house labor, etc. Cost savings can be achieved by targeting excavations directly on possible features, thereby reducing the overall amount of excavation needed to evaluate a site. Here one must exercise considerable care in prioritizing anomalies for excavation. If the amount of excavation can be reduced, additional savings can be achieved as a result of the need to analyze and curate fewer artifacts. Nevertheless, the addition of geophysics to one's NRHP eligibility assessment program is unlikely to reduce overall costs on a site by site basis. Instead, the primary benefit of using geophysics will be the enhanced quality of information about the sites.

The potential for cost savings can be seen, however, when the benefits of geophysics are viewed from a programmatic perspective. For example, most archaeologists are aware of the limitations of traditional approaches to site evaluation. Traditional NRHP evaluations based on small scale excavations often fail to identify features or other important deposits, therefore significant resources may be inadequately protected. To offset such risks, many cultural resource managers, CRM consultants, and State Historic Preservation Office personnel prefer to "err on the side of caution". At military installations or in state or national forests, sites may be avoided because they *may* include scientifically or culturally important deposits. Resource managers rarely calculate the actual costs of protecting sites that, in fact, don't warrant such protection, but those costs can be significant. This is particularly true, for example, at military installations where large continuous areas are essential for realistic military training. Properly used, geophysics can help managers make more informed, responsible decisions about site management, protecting important sites, but not expending scarce resources on the protection of marginal sites.

Substantial cost savings can be achieved if geophysics is integrated into site mitigation programs. Serious impending impact to an NRHP-eligible site caused by construction activities or other undertakings often results in a mitigation program. For archaeological sites this frequently involves a program of large-scale excavations, data analysis, and dissemination of a comprehensive report. Mechanized stripping of the plow zone followed by hand excavation of features is a cost effective approach practiced in some states. That approach is not used in many regions, and may not be suitable for sites located in wooded areas, where features occur at varying depths below the plow zone, or where human remains may be present. In such cases, geophysical survey can identify areas with features, reducing the overall amount of hand excavation needed.

In summary, an effective use of geophysics can enhance the reliability of NRHP evaluations, and reduce costs associated with large scale hand excavations during site mitigation projects. Geophysics can provide resource managers with more complete information about subsurface deposits, thereby reducing the need to manage (i.e., avoid) sites that "may" include important deposits. These potential advantages can also benefit those involved in non-compliance driven research. Geophysical surveys can provide the information needed to develop more sophisticated sampling strategies, and can help detect the types of features (e.g., prehistoric houses) likely to provide data needed to address particular research questions about culture history, site function, demography, and other interests. In addition, the use of large-area geophysical surveys can reveal the spatial layout of sites (e.g., use of domestic and ritual space, village organization, and other spatial patterns), a scale that is rarely afforded by excavations alone. In all applications, however, the potential benefits of geophysics can only be achieved when appropriate sensors and methods are used, data quality is optimized, and interpretations are evaluated using independent (ground truthing) evidence.

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