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## Magnetometer Prospecting in Historical Archaeology: Evaluating Survey Options at a 19th-Century Rancho Site in California

### ABSTRACT

To complement the growing literature on magnetic prospection in historical archaeology, the practical aspects of magnetometer selection and survey design need to be explored. Based on a test case from the Petaluma Adobe State Historic Park in northern California, two readily-available magnetometers are compared with respect to instrument type (alkali-vapor versus proton precession), sensor configuration and number (total field versus vertical gradient), sensor height, intensity of data collection, and basestation correction procedures. These variables are then considered in light of survey speed, labor input, and monetary cost. Results indicate that the alkali-vapor gradiometer is better suited for historical archaeological research based on survey speed and efficiency, volume of data collected, temporal and spatial intensity of station readings, and sensor sensitivity. In addition, the data reconfirm the importance of sensor height, gradiometer configuration, and basestation correction in obtaining high-quality magnetic data.

### Introduction

The value of geophysical survey in archaeology has been demonstrated in a variety of research contexts, spanning academic and cultural resource management domains and both historical and prehistoric periods. Though remote-sensing methods have been applied extensively in prehistoric archaeology in the United States, the importance of these techniques for historical archaeology cannot be understated. Given that historical archaeologists consistently focus on recovering and understanding the built environment and spatial layout of sites, geophysical techniques can be essential components of the archaeological "toolkit." Since historical archaeology can involve much more than architectural remains, geophysical survey methods provide

cost-effective and rapid means for obtaining a preliminary view of the subsurface features, site structure, and architecture of both large and small sites. In other words, they allow a non-invasive way of discovering and evaluating cultural resources.

One of the central instruments in these geophysical endeavors has been the magnetometer, a device now entering its fifth decade of use in archaeological research. Following the pioneering work in the 1950s and 1960s (Aitken 1958, 1959a, 1959b; Aitken et al. 1958; Lericci 1961; Scollar 1961; Aitken and Tite 1962; Black and Johnston 1962; Hall 1962; Alldred 1964; Breiner 1965; Tite 1966), the application of magnetometry in archaeology has reached sizable proportions, especially in Europe. This can be seen in general works on geophysical prospecting (Lington 1963:54-55; Weymouth 1986:343-369; Scollar, Tabbagh, et al. 1990:375-519; Clark 1996:64-98), on comparisons between magnetometers and other geophysical surveying instruments (Blundell et al. 1974; Parrington 1979; Farnsworth 1980, 1982; Tabbagh 1984; Weymouth and Woods 1984; Tabbagh et al. 1988; Martin et al. 1991; Arnold et al. 1997), and on specific magnetometer applications (Breiner and Coe 1972; Becker 1983; Von Frese 1984; Von Frese and Noble 1984; Garrison et al. 1985; Gibson 1986; Abbott and Frederick 1990; Bevan 1991; Brock and Schwartz 1991; Farnsworth and Mueller 1992a, 1992b; Frederick and Abbott 1992; Larson and Ambos 1997; Crawford and Larson 1998). Many of the previous citations that focus on North American sites are projects in historical archaeology (Garrison et al. 1985; Von Frese 1984; Von Frese and Noble 1984; Weymouth and Woods 1984; Farnsworth and Mueller 1992a, 1992b). In addition, the bulk of magnetometer work reported in United States cultural resources management literature has been conducted by historical archaeologists. It is for these two reasons that the specifics of magnetometer use need to be further considered within historical archaeology.

Although archaeologists have made brief comparisons between different magnetometers (Clark 1996:66-70; Arnold et al. 1997:159-160; Larson

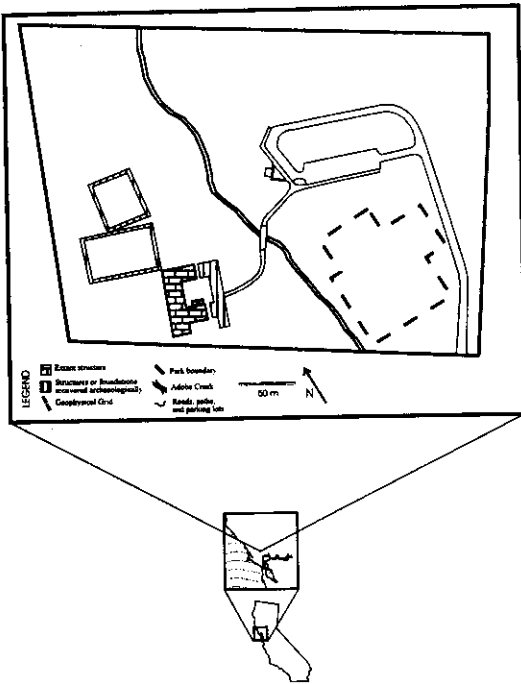


Figure 1. Petaluma Adobe State Historic Park, Petaluma, California. Shown within the State Park boundaries are the geophysical grid, the archaeological and historical structures, and the extant park facilities and features.

and Ambos 1997:13-14), very few have published the results of explicit comparisons (Tite 1961; Ralph 1964). It has been argued that the alkali-vapor magnetometer's higher density of readings and greater sensitivity allow identification of archaeological features that may have been missed by proton magnetometer surveys, but there has been no explicit test of these assumptions. Since the sensitivity of archaeological materials to magnetometry is dependent on the magnetic properties of the soil, the density of spatial sampling during magnetometer surveying, and the use of single-sensor magnetometers or dual-sensor gradiometers, a focused study is needed to evaluate the relative strengths and weaknesses of magnetometers by type, configuration, and use.

The objective of this paper is to consider pragmatic issues in selecting and using magnetometers in historical archaeology. The goal is not to provide detailed interpretation of the particular case study but rather to use the case study as a springboard for discussing the practical issues surrounding magnetometer selection

and use. The process involves comparing the use of different magnetometers under variable operating conditions. Comparisons here center on the two most readily-available magnetometer types in the United States: the proton-precession and the alkali-vapor. Based on three different surveys with the two instrument types, issues of data quality, practicality, and cost can be addressed in relation to the use of magnetometers in historical archaeological research. The hope is that more empirical data on magnetometer options will facilitate better choices in the field.

The work begins by outlining a case study in geophysical prospection and historical archaeology at the Petaluma Adobe State Historic Park in northern California. After outlining the study area, the paper highlights briefly the central tenets of magnetometry, and it introduces the two types of magnetometers to be compared, the data processing steps, and the basestation correction procedures. The next section outlines the results obtained from the three distinct surveys conducted with these two instruments. The final section discusses the field strategies employed to treat the variables of magnetometer type (alkali-vapor versus proton precession), sensor configuration (gradiometer versus total field), sensor heights, intensity of data collection, and basestation correction. These results are then considered in relation to the practical aspects of survey costs and implementation.

### Study Location

The Petaluma Adobe State Historic Park is located northeast of Petaluma, California (Figure 1). The park currently protects 41 acres of the once vast 19th-century Mexican-Californian rancho owned and operated by Mariano G. Vallejo. Vallejo was an influential political and military figure in the 1830s and 1840s, especially in the region just north of San Francisco Bay (McKittrick 1944; Rosenus 1995). The Mexican-Californian rancho survived as a colonial operation through livestock raising and butchering, hide and tallow processing, agricultural production, and goods manufacture (Greenwood 1989). The labor force for these activities, especially on large ranchos such as the Rancho Petaluma (Davis 1929; Vallejo 1941; Hoopes 1965), was composed almost exclusively of Native Americans. The laborers performed these duties, under

the direction of labor overseers, for rancho self-sustenance and for external trade. The main structure on the Rancho Petaluma still stands—a large, two-story adobe building that covered almost 3600 m<sup>2</sup> while in use, though only half remains today. Whether or not the “missing” half was ever fully completed is still an unresolved issue (Treganza 1958; Hoopes 1965). In addition to this building, known as the Petaluma Adobe, the only other known structures on the rancho are represented by two foundations uncovered to the northwest of the main adobe (Clemmer 1961; Gebhardt 1962) and a small quadrangle-shaped foundation across the stream in a nearby field (Gebhardt 1962). The former are believed to be corrals (Clemmer 1961).

To complement the preliminary archaeological work completed during the state acquisition of the park lands (Treganza 1958; Clemmer 1961; Gebhardt 1962), the senior author developed, in collaboration with State Park archaeologists and historians, an archaeological project to investigate aspects of this 19th-century operation (Silliman 1997, 1998). The specific objective was to locate the residential and activity areas associated with the Native American rancho laborers. In doing so, the project directed efforts away from the extant adobe structure of the rancho owner and labor overseer and into the open spaces surrounding the main house. The multiphase project began in 1996 with pedestrian and geophysical survey in the state park and has culminated in a series of trench and block excavations in a field across the stream from the Petaluma Adobe. This is the same field in which the foundation was discovered in 1961 (Clemmer 1961) and in which two buildings are reputed to have stood, based on a 19th-century survey map (O’Farrell 1848). The exact location of these two, or three, structures is currently unknown.

In general, few historical documents exist that detail the living and working areas for native people at the rancho (Hoopes 1965). Therefore, the task of locating these areas rested solely on archaeological methods, a situation that proved ideal for using geophysical survey. Initial efforts by the senior author involved geophysical surveys with both a Geometrics 858 Cesium Gradiometer and a Geonics EM-38 Electromagnetic Conductivity Meter. For the purposes of this paper, only the former’s results will be considered here, though both had significant

success as confirmed by later archaeological testing and full-scale excavation. The broad-scale excavation revealed extensive historical midden deposits, large concentrations of bone and domestic refuse, and various pit and rock features (Silliman 1999). Not unexpectedly, the magnetometer proved effective at detecting pits of charcoal and burned faunal remains, extensive thermally-altered stone features, and accumulations of igneous stream cobbles. In the end, the magnetometer survey not only helped narrow down the rancho acreage for excavation purposes but also improved the interpretation of site structure and native use of space at this historical site. This ability is especially important at historical sites containing a Native American presence because of the potential lack of definitive architectural remains. Because of the high-quality data obtained with the gradiometer survey and because of subsequent ground-truthing through excavation by the senior author, the potential to test different magnetometer instruments and surveying procedures as part of the overall field program was recognized.

## Methods

The specifics of magnetometry and magnetometer surveying in archaeology have received substantial treatment in the literature. Therefore, it will suffice to discuss only briefly the physics of magnetic detection and the nature of magnetometer instruments, drawing heavily from summaries in Weymouth (1986) and Clark (1996). Detailed, quantitative discussions can be found in Aitken (1974:207-265) and Scollar, Tabbagh, et al. (1990:450-466). The magnetometry technique entails the principle of detecting differences, or anomalies, in the earth’s known magnetic field at any given point at or near ground surface. The field strength of the anomaly is a function of the distance ( $r$ ) from the source to the sensor, varying in magnitude as  $1/r^3$ .

The localized magnetic fields result from remanent or induced magnetism. Remanent magnetism is the permanent magnetization of an object due to its mineral composition and/or thermal history, while induced magnetism is a function of an object’s susceptibility to being magnetized. Igneous rocks, thermally-altered stones, or fired clays typify examples of remanent magnetism; ferrous objects best illustrate

induced magnetism, though they have remanent magnetism as well. In addition to specific objects or features, most sediments of natural origin contain magnetic minerals, though they vary in magnetic susceptibility due to the presence of iron compounds such as magnetite and hematite. These allow localized features such as trenches, pits, walls, or graves to be distinguishable from the surrounding soil because of magnetic contrast between the anthropogenic disturbance and the undisturbed soil. This context is often set by soil formation processes (Tite and Mullins 1971).

The four primary kinds of magnetometers are proton precession, alkali-vapor, fluxgate, and Overhauser. The fluxgate and Overhauser models are popular in Europe (Tite 1961; Allred 1964; Clark 1975, 1996:69-78), but they have not been used extensively in the United States, although this pattern is changing. On the other hand, the proton-precession and alkali-vapor instruments remain the most popular and readily available magnetometers in North America. The proton precession instrument has been the archaeological standard for decades, but the alkali-vapor has become a popular choice in the last few years. Because of this popularity and the limited availability of Overhauser and fluxgate instruments, our discussion and test comparisons encompass only the alkali-vapor and proton-precession instruments.

### *Instrumentation*

The specific variables of archaeological magnetometry to be evaluated are: (1) magnetometer type (alkali-vapor versus proton precession), (2) sensor configuration (gradiometer versus single-sensor), (3) sensor heights, (4) intensity of data collection, and (5) basestation correction procedures. These five variables can then be integrated into a general consideration of survey quality, efficiency, and cost. The three magnetometer types tested in this study are an alkali-vapor (Geometrics 858 Cesium) gradiometer, an alkali-vapor (Geometrics 858 Cesium) magnetometer, and a proton precession (Geometrics 856AX) gradiometer. The use of Geometrics' models is not meant to endorse this particular brand at the expense of others such

as GEM Systems, Geoscan, Varian, and Scintrex (now Intelligent Detection Systems). Rather, the choice was based on the common use of these magnetometers in North American archaeological practice, our prior experience with the particular models, and Geometrics' willingness to loan instruments for some of our research. A comparison of *all* brands and types of magnetometers is beyond the scope of this paper.

The alkali-vapor magnetometer/gradiometer is characterized by a sensitivity of 0.05-0.01 nanoteslas (nT), cycle times of up to 0.1 second, heading errors of less than  $\pm 1$  nT, and continuous or discrete measurement modes. The instrument comes equipped with an electronic console mounted on the waist that allows an operator to define and edit the survey grid, accurately record and alter position within the grid, and monitor magnetic data as they are collected. Following the manufacturer's design, basic survey procedure involves carrying the sensor on a staff oriented parallel to the ground surface and supporting the apparatus with a shoulder strap. The alkali-vapor magnetometer and alkali-vapor gradiometer differ only in the addition of a second sensor in a vertical array for the latter. The operator determines the sensor separation and orientation, though maximum possible separation given the current design is less than 1 m. Sensor heights are dependent on the user's stature and shoulder strap adjustment. A separate vertical staff held by a second operator can also be designed and used for more accurate sensor placement.

The proton precession magnetometer/gradiometer specifications include a sensitivity of 0.1 nT and discrete measurement mode. The readings are stored in digital form, and they can be reviewed in the field as individual measurements per station numbers, which increase in simple increments from the beginning of the survey to the end. In the vertical gradiometer mode, which is the one utilized in this study, the two sensors read sequentially, rather than simultaneously, with an approximate 2-second delay. The sensor separation of 0.85 is relatively inflexible in the manufacturer's design, with the two sensors (measured from center) set at approximately 0.70 m and 1.55 m above the ground. The instrument sensors on the vertical staff are held by one operator, while the data

storage unit is carried by a second operator at a distance determined by the data cable length, usually less than 2 m.

For both instruments, the survey method involved staking out a grid, marking nylon ropes at 1 m intervals with non-magnetic tape and flagging, laying "base line" ropes along the top and bottom (relative to y-axis) of the survey grid, and placing the survey line rope perpendicular to the base line ropes. The operator then surveyed parallel to and directly over the survey rope lines. After the completion of each surveyed line, the ropes were moved to the next survey line position. The marked ropes assisted discrete surveys by allowing quick placement of the magnetometer sensors without use of unwieldy tape measures, and they helped continuous surveys by allowing the operator to coordinate pacing and sensor location with the reading cycle of the magnetometer. To control for any possible operator error, the same individual operated the magnetometer in all alkali-vapor magnetometer surveys, and another same-operator duo (one holding the staff, one acquiring the readings in the data-recorder) ran the instrument in the proton precession gradiometer survey.

### Survey Cases

The first survey (Survey One) involved a large-scale alkali-vapor gradiometer survey of 8,000 m<sup>2</sup> at the Petaluma Adobe State Historic Park in June 1996 by the senior author. The particular field selected was chosen because of two presumed, though not visible, mid-19th-century adobe structures and the surface expression of an historic-period native midden (Treganza 1958; Silliman 1998). The gradiometer survey detected numerous and extensive magnetic anomalies in the field hypothesized to be the 19th-century native living and working area, and many of these anomalies have been recently ground-truthed through excavation.

A subset of the main 8,000 m<sup>2</sup> grid was selected for iterative surveys in Fall 1997. Survey Two involved the use of an alkali-vapor magnetometer and two different basestation methods, and Survey Three involved the use of a proton precession gradiometer. Out of the total area, a 400 m<sup>2</sup> block (5%) was selected where subsurface excavation had not yet been

initiated. The choice hinged on four factors: (1) the earlier gradiometer survey, as this survey had demonstrated that the block contained an array of anomaly shapes, strengths, and definition; (2) adjacent excavated trenches from the Summer of 1997, which were conducted in part to test the archaeological entities responsible for the specific magnetic targets; (3) the relatively low vegetation cover and topographic relief, and (4) the negative results from a cursory metal detector survey, obviating the problem of *surface* iron debris (Weymouth 1986:347).

### Data Processing

All data were processed, displayed, and analyzed in Golden Software's SURFER 6.0. Although archaeologists commonly present magnetometer data as iso-intensity contours, most simple line contour maps of magnetic readings can be difficult to decipher, especially if the data have not been despiked nor filtered. Our experiences suggest that a satisfactory method for visual interpretation is a filled contour map with the actual contour lines made invisible, rendering a result similar to gray-scale. Similarly, other archaeologists have argued that gray-scale images, rather than contour maps, provide magnetic results more amenable to visual analysis by better isolating aspects of linear and complex features (Scollar 1969:77; Scollar, Weidner, et al. 1986:623). Magnetometer data presented here involved nearest neighbor gridding and no filtering operations. Gradient data were calculated by subtracting the lower sensor reading from the upper sensor reading and dividing by the distance between sensors.

Basestation correction followed the procedure included in the magnetometer software. The magnetometer software allows a user to open both a survey file and a basestation file, the latter from either an alkali-vapor magnetometer console or a lone proton precession magnetometer, and export them together to an X, Y, Z file format in SURFER. The software interpolates between all available timed readings in the basestation file to insure enough values to correct every reading gathered in the survey file, and the result is a diurnal correction value. This number is computed by subtracting the basestation reading from the raw magnetometer survey reading, and then by either adding a

user-defined value or the average of the two for the first survey line. The former proved appropriate for this study.

## Results

### *Survey One*

As introduced above, the first survey in this project was a large-scale alkali-vapor gradiometer survey of 8,000 m<sup>2</sup> at the Petaluma Adobe State Historic Park conducted by the senior author. Magnetometer surveys were conducted in an east-west direction with survey line spacing (distance between survey lines) equal to 1 m and in-line spacing (distance between readings along each line) equal to 0.05 m. The latter was achieved with continuous cycling at 0.1 second and an operator pace of 0.5 m/second with fiducial marks inserted every 5 m to provide accurate locational data. Sensor separation was 0.75 m with the upper sensor center at approximately 1.2 m above the ground surface and the lower sensor center at approximately 0.45 m above the ground surface. These are approximate heights as the operator carried the instrument with the shoulder strap; thus, it is subject to slight shifts while surveying depending on grass height or topographic undulations. Being a gradiometer, no basestation readings were necessary.

The results for Survey One suggest a large number of anomalies across the entire 8,000 m<sup>2</sup> survey area (Figure 2). The complexity of magnetic anomalies and the large number of stations readings across the grid area precluded fine-scale contouring by SURFER when the in-line spacing was 0.05 m. To produce an image from the high volume of magnetic data, even one with relative large contour intervals (>10 nT/m), it was essential to reduce the number of station readings by only plotting every 10th line. This procedure created an effective in-line spacing of 0.5 m. Consequently, the final image displays an in-line spacing of 0.5 m and a contour interval of 7 nT/m. The blank area in the SW corner of the survey grid blocks a concentration of high magnetic gradients found over a gas main trending NW-SE across the grid corner. As stated above, only a small section of this survey grid—bounded by 30s 10w, 30s 0w, 70s 0w, 70s 10w—constitutes the magnetometer

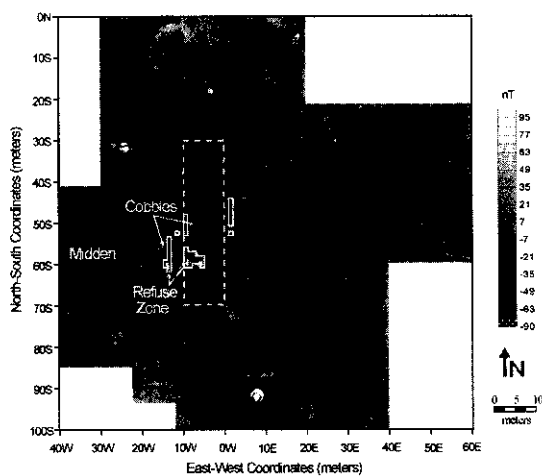


Figure 2. Alkali-vapor gradiometer image for complete survey grid. The broken-line rectangle within the larger grid represents the 400 m<sup>2</sup> subgrid extracted for this paper; the solid-line rectangles show the locations of trench and block excavations in summer 1997 and 1998 that are relevant to this paper. Data reflect 1 m line and 0.5 m in-line spacing, 7 nT/m contour intervals, and a range of -90-95 nT/m. The highest and lowest values have been pushed to null because their spikes drown the more subtle magnetic variability.

assessments in this paper, but it is necessary to summarize some of the excavation results conducted subsequent to this initial survey to bracket the test grid.

Given the relatively homogenous nature of the clay/silty clay loam alluvium comprising the entire survey area, the vast majority of magnetic anomalies are presumed to be cultural features and natural stream deposits of igneous cobbles. The many activities reputed to have occurred at this rancho site in the 19th century would have produced a wealth of archaeological features, but since this paper is focused solely on the pragmatics of magnetometer surveying, an in-depth interpretation of this magnetic survey is not necessary here. Suffice it to note that excavation in the center of the geophysical grid (Figure 2) produced a refuse zone with various features involving fire-cracked rock, unburned faunal remains, and artifacts such as obsidian bifaces and projectile points, obsidian and chert debitage, historic ceramics, bottle glass, nails and other metal objects, and glass beads (Silliman 1999). Additionally, the excavation area on the western edge of the full grid produced a dense 19th-century midden that included glass beads;

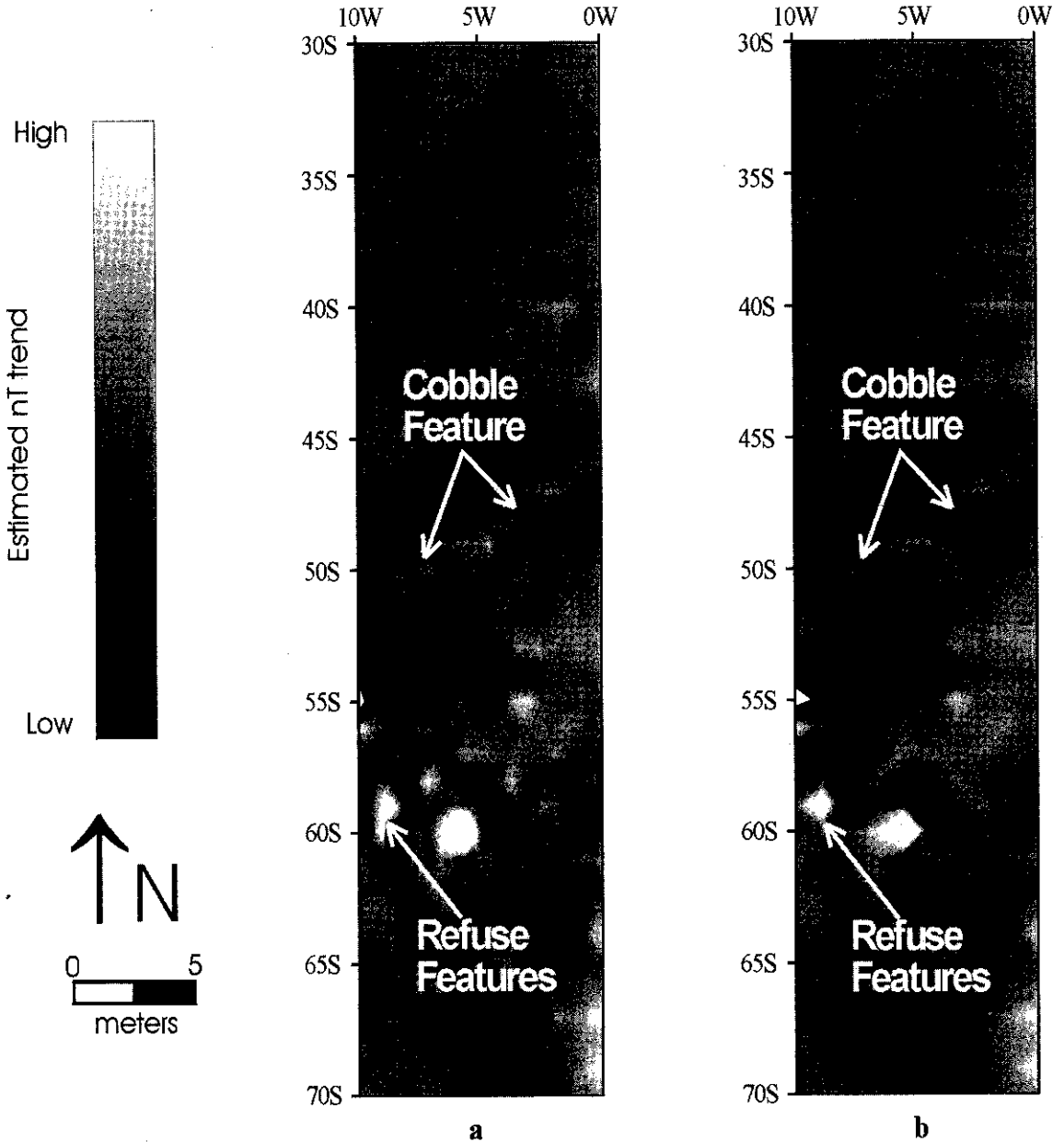


Figure 3. Comparison of alkali-vapor gradiometer images by resolution. The nT contour scale is only an estimated trend scale rather than an actual value scale, since the purpose is image comparison: *a*, alkali-vapor gradiometer, 1 m line and 0.05 m in-line spacing, 0.75 nT/m contour interval, range of -50-50 nT/m; *b*, G-858 alkali-vapor gradiometer, 1 m line and 0.1 m in-line spacing, 0.5 nT/m contour interval, range of -35-50 nT/m.

obsidian and chert lithics; groundstone fragments; nails and various iron buckles and buttons; bottle glass sherds; refined earthenware, porcelain, and stoneware sherds; and vast quantities of burned and unburned faunal elements (Silliman 1999).

One of the more interesting magnetic targets was the linear, narrow feature trending SW-NE in the center of the image (Figure 2), as this

initially suggested potential remnant adobe walls and/or cobble foundations (Silliman 1997, 1998). Subsequent excavation has revealed that this cobble feature is in fact part of a suite of fluvial deposits directly underlying the historic-period cultural deposits. These stones express high magnetic signatures because they are primarily igneous in origin. Though this feature appears

to be non-cultural, the magnetic signature should be comparable to that produced by a cobble footing made of similar igneous stones.

In addition to the cobble stream feature, excavation has revealed the magnetically-strong, semi-circular feature centered over 60s 15w to be a large cobble and bone feature containing extensive thermally-induced fracturing and an underlying 3-5 cm band of charcoal and fire-cracked rock. These two characteristics suggest that the feature had a variable thermal history.

Furthermore, the complexity of anomalies contained in and extending westward from the southern half of the test grid appear to be a variety of pits of burned material, collections of thermally-altered or large igneous cobbles, or clusters of iron artifacts. Excavation in 1998 following the magnetometer surveys revealed one of these anomalies in the vicinity of 58-61s 8-10w inside the test grid (Figure 2). This feature was an accumulation of refuse that consisted of unburned and often articulated faunal elements, thermally-affected stones, unmodified cobbles, charcoal, and a mixture of artifacts. The latter included lithics, ceramics, beads, glass, and metal, although the metal did not appear in large quantities.

Figure 3 contains the images to be compared from the 1996 gradiometer surveys. A new contour map (Figure 3a) was generated from the alkali-vapor gradiometer survey to provide better resolution of the anomalies since the number of station readings and contour complexity diminished by several orders of magnitude from the 8,000 m<sup>2</sup> survey. The revised image of the test grid has 0.05 m in-line spacing, as recorded in the field, and a contour interval of 0.75 nT, both of which provided maximum possible resolution for the survey data. As such, much more detail on anomaly occurrence, shape, and boundaries is visible here than in the earlier, less-resolved image (Figure 2). In addition, a second image (Figure 3b) was generated for comparative purposes at a resolution identical to that produced by the proton precession gradiometer (noted below): 1 m in-line station spacing and 0.5 nT contour intervals. In both images, the key magnetic features are (1) the linear magnetic high running NE-SW (from 45s 0w to 52s 10w), known through adjacent excavation to be the fluvial cobble deposit; (2) the complex array of positive and negative anomalies south of

this linear feature to approximately 59s, some of which have been revealed through excavation to be various features of thermally-altered material and historical bone and artifact refuse (noted above); (3) the magnetic high in the SE corner (68-70s 0-1w) that has not been excavated; and (4) the two lower-level but still noticeable anomalies in the north (39-40s 1-2w) and NE (33-34s 4-7w) sections, neither of which have been ground-truthed.

### *Survey Two*

Following the selection of the test grid detailed above, the 400 m<sup>2</sup> block (Survey Two) was surveyed in September 1997 using the alkali-vapor magnetometer. For consistency with Survey One, the survey proceeded at a line spacing of 1 m. Fortunately, the low vegetation allowed a surveying pace of 1 m/s and a corresponding in-line sampling rate of 0.1 m with cycle time at the maximum 0.1 s. No fiducial marks were necessary because the east-west survey line was only 10 m in length. Sensor height was approximately 0.85 m above the ground, given the height of the operator and the shoulder-strap configuration.

During this survey, the survey team compiled two different basestation files: (1) a proton precession magnetometer stationed off the survey grid cycling every 5 seconds and (2) an internal basestation file within the alkali-vapor gradiometer being triggered every 5 minutes at a selected coordinate point within the 400 m<sup>2</sup> grid. The latter procedure involved choosing a relatively quiet magnetic location (as based on the earlier alkali-vapor gradiometer survey), taking a discrete ("triggered") reading at the location prior to beginning the survey, returning to the location every 5 minutes to take discrete readings, and acquiring a final reading at the location upon the completion of the survey. The results of the alkali-vapor magnetometer (Figure 4a) appear comparable to, though much less resolved than, the alkali-vapor gradiometer (Table 1). Because of the small grid area, full data resolution could be achieved with 0.1 m in-line spacing (as recorded in the field) and 0.5 nT contour intervals.

The alkali-vapor magnetometer image displays the same linear feature trending SW-NE as does the one from the alkali-vapor gradiometer, but



TABLE 1  
COMPARISON OF MAGNETOMETER DATA RESOLUTION BY INSTRUMENT TYPE AND SENSOR HEIGHT

Instrument Type & Sensor Height	Instrument Type and Sensor Height <sup>a</sup>						
	G858, 1.2m	G858, 0.85m	G858, 0.45m	G858-Gr, 0.45m	G856, 1.55m	G856, 0.70m	G856-Gr, 0.70m
G858, 1.2m	-	Slightly Worse	Worse	Worse	Compa- rable	Slightly Worse	Worse
G858, 0.85m	Slightly Better	-	Slightly Worse	Slightly Worse	Better	<i>Slightly Better</i>	<i>Compa- rable</i>
G858, 0.45m	Better	Slightly Better	-	Slightly Better	Better	Better	Better
G858-Gr, 0.45m	Better	Slightly Better	Slightly Worse	-	Better	Better	Better
G856, 1.55m	Compa- rable	Worse	Worse	Worse	-	Slightly Worse	Worse
G856, 0.70m	Slightly Better	<i>Slightly Worse</i>	Worse	Worse	Slightly Better	-	Slightly Worse
G856-Gr, 0.70 m	Better	<i>Compa- rable</i>	Worse	Worse	Better	Slightly Better	-

#### Notes

The table provides a one-to-one data comparison of the two instruments and various sensor heights discussed in the paper. It should be read from row to column (i.e., the row magnetometer data is . . . than the column magnetometer data). The gradiometer data are shown with the height of the lower sensor so that data may be viewed as the lower sensor filtered by the upper sensor (details in text). The italicized entries run counter to the expected correlation between data resolution and sensor height.

<sup>a</sup>Gr = gradiometer, 6858=alkali-vapor, 6856=proton precession.

its exact form is less clear. The magnetic low north of the linear cobble bed exists in both images, but the exact definition of the cobble feature itself, as known through adjacent excavations, is masked in the alkali-vapor magnetometer image. In addition, the resolution of small anomalies within the central/south-central section of the grid diminished in the total field alkali-vapor magnetometer survey. The relative magnetic high of these areas is visible, but the internal details are not readily detectable. Moreover, there appears to be a slight alternate line smearing of magnetic readings, though these do not detract from the overall interpretability of the image. In addition to the linear feature, the alkali-vapor magnetometer survey detected the same larger positive anomalies located by the alkali-vapor gradiometer along the north edge, NE corner, and SE corner.

As a complement to Survey Two's sensor height of 0.85 m, the magnetic readings from the 1996 alkali-vapor gradiometer survey supplied another avenue of analysis. Instead of using the gradient between the two sensors, we extracted separately and contoured the readings for the upper and lower sensor. The data are equivalent to an alkali-vapor magnetometer survey at 1.2 m sensor height (Figure 4b) and at 0.45 m sensor height (Figure 4c), respectively (Table 1). These results were compared to those of the single-sensor alkali-vapor magnetometer survey discussed above (Figure 4a). Without question, both sensors detected the large-scale anomalies present below the ground surface, but the lower sensor (Figure 4c) better recorded the micro-scale anomalies.

As summarized in Table 1, the alkali-vapor gradiometer's lower sensor (Figure 4c) compares

favorably in data resolution to the alkali-vapor gradiometer. At least for expected shallow deposits (less than 1 m below ground surface), this reconfirms that the lower the sensor, the more attune the instrument is to small-scale and near-surface anomalies (Weymouth 1986:347; Frederick and Abbott 1992:151; Herwanger 1996:23-24). Similarly, the higher sensor is more restricted to delineating broad scale features of magnetic contrast and serves as a high-pass filter. In this way, the adjusted difference between the two sensors (i.e., the gradient) can be seen as the lower sensor's readings being corrected for the diurnal or other temporal variations and for the large-scale geological anomalies detected by the upper sensor. Interestingly, the large ambient disruptions in the south end of the

survey grid in Figures 4b and 4c suggest that a major magnetic disturbance affected the sensors during the survey of these lines. The disruption influenced both sensors simultaneously and comparably, and the resulting gradient between the two, as shown in Figure 3, was compatible with the surrounding non-disturbed data points.

### Survey Three

For Survey Three, the 400 m<sup>2</sup> block was surveyed in September 1997 using the proton precession gradiometer. As before, the survey line spacing was 1 m, but because the instrument takes discrete readings and has a 5+ second cycle time per two-sensor reading, the in-line spacing was adjusted to 1 m. Such an in-line

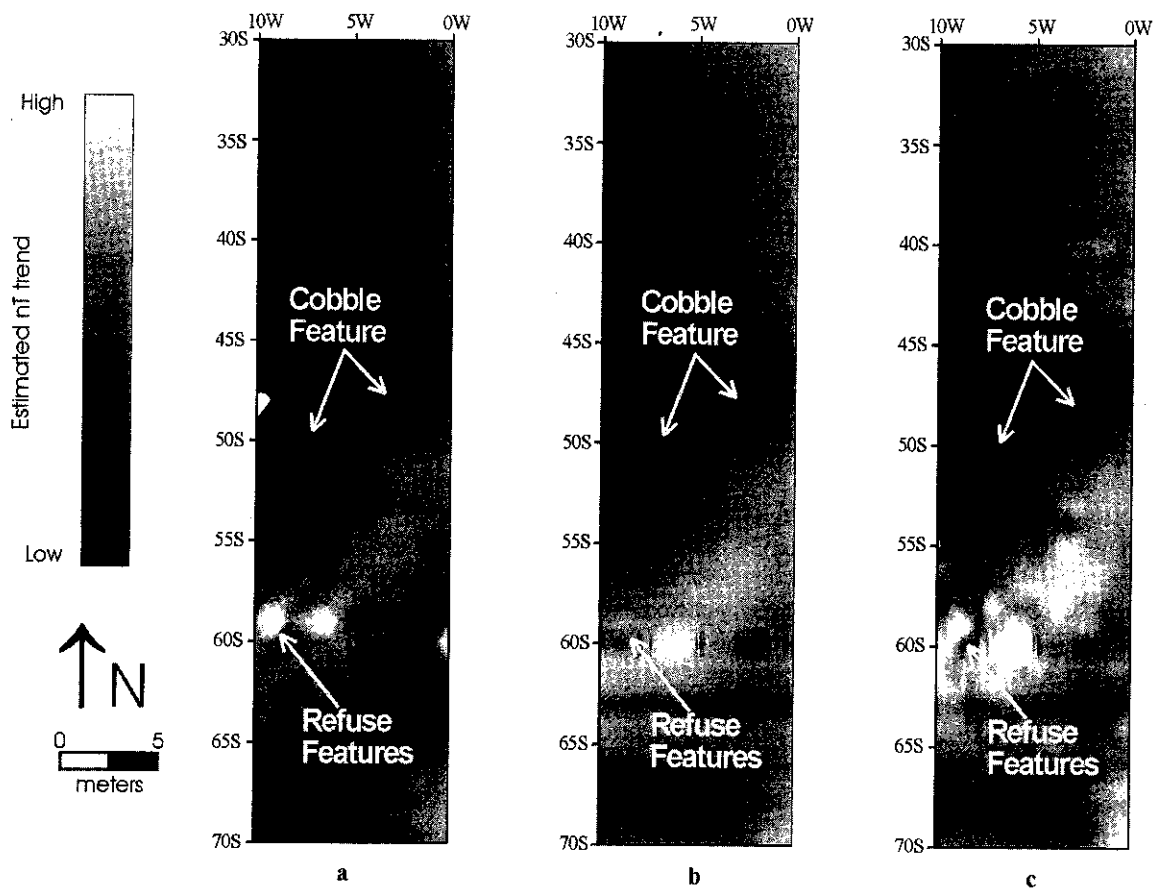


Figure 4. Comparison of alkali-vapor magnetometer images by sensor height. The nT contour scale is only an estimated trend scale rather than an actual value scale, since the purpose is image comparison: a, alkali-vapor magnetometer with 0.85 m sensor height, 1 m line and 0.1 m in-line spacing, 0.5 nT contour interval, range of 50,199-50,328 nT; b, alkali-vapor gradiometer with only upper sensor represented at 1.2 m height, 1 m line and 0.1 m in-line spacing, 0.5 nT contour interval, range of 50,290-50,408 nT; c, alkali-vapor gradiometer survey with only lower sensor represented at 0.45 m height, 1 m line and 0.1 m in-line spacing, 0.5 nT contour interval, range of 50,390-50,408 nT.

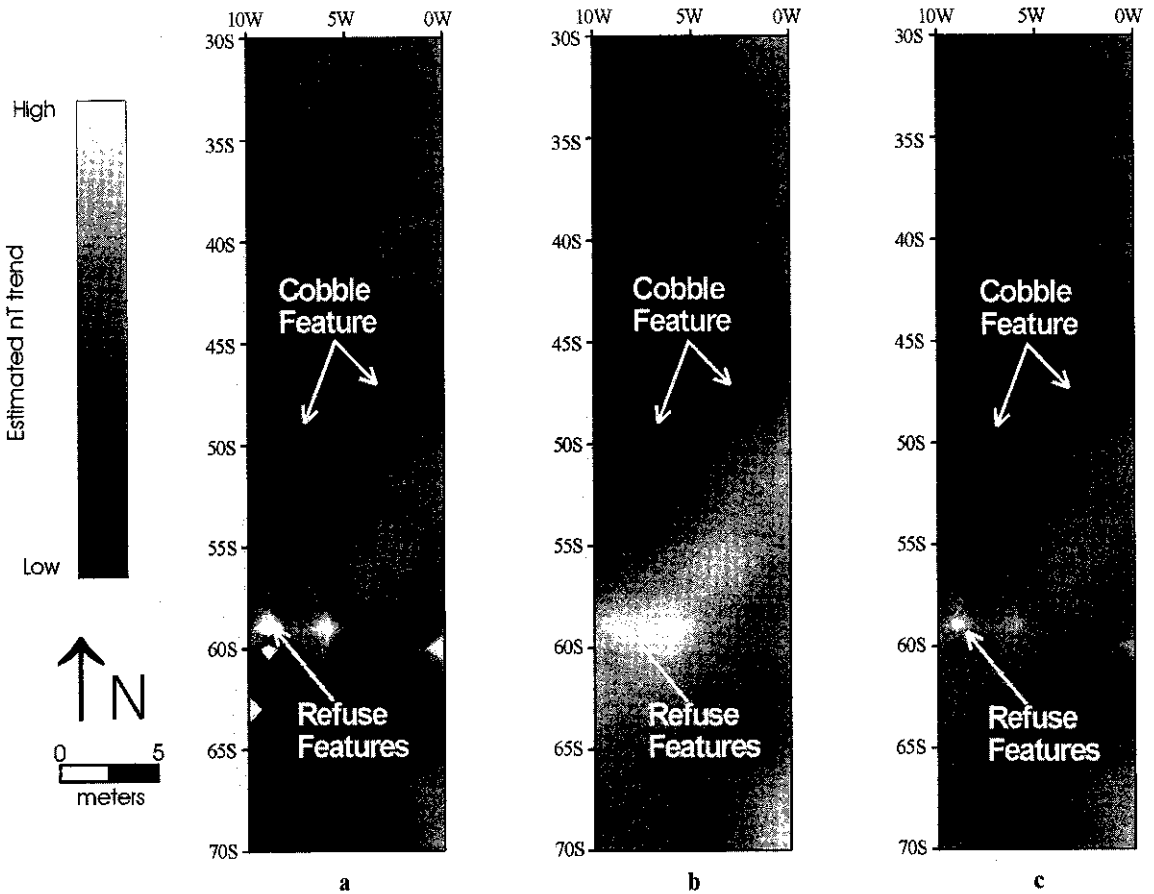


Figure 5. Comparison of proton precession gradiometer and proton precession magnetometer (lower sensor of proton precession gradiometer). The nT contour scale is only an estimated trend scale rather than an actual value scale, since the purpose is image comparison: *a*, proton precession gradiometer, 1 m line and 1.0 m in-line spacing, 0.5 nT/m contour interval, range of -35-50 nT/m; *b*, proton precession magnetometer with 1.5 m sensor height (created by extracting upper sensor from proton precession gradiometer survey), 1 m line and 1.0 m in-line spacing, 0.5 nT contour interval, range of 50,223-50,307 nT; *c*, proton precession magnetometer with 0.75 m sensor height (created by extracting lower sensor from proton precession gradiometer survey), 1 m line and 1.0 m in-line spacing, 0.5 nT contour interval, range of 50,173-50,384 nT.

spacing is common with archaeological surveys using the proton precession model. Similar to Surveys 1 and 2, the survey aligned on an east-west axis. As discussed above, the sensor separation was 0.85 m with the upper and lower sensor centers at 0.70 m and 1.55 m, respectively. No basestation readings were gathered because of the gradiometer's dual sensors.

The results of the proton precession gradiometer survey produced an image with anomaly resolution between the previous two survey results (Figure 5a). As with the alkali-vapor single- and dual-sensor magnetic surveys, the proton precession gradiometer detected the linear

cobble anomaly, the complex array of anomalies south and west of this feature corresponding to the historical refuse feature, and the three moderately-sized anomalies in the north, NE, and SE edges of the image. Similar to the alkali-vapor gradiometer survey, the proton precession gradiometer achieved better resolution of anomalies, especially in the definition of edges and shapes, than the alkali-vapor magnetometer at both 0.85 and 1.20 m sensor heights (Table 1). The proton precession gradiometer could not achieve, however, the resolution capable with the lower sensor of the alkali-vapor gradiometer. Although the effective center of the proton pre-

cession gradient (1.15 m) matched or exceeded the middle and upper alkali-vapor magnetometer sensor positions, the lower sensor of the proton precession gradiometer was a full 0.15 m closer

to the ground surface and had the benefit of a high-pass filter through the upper sensor. This sensor height also accounts, at least partly, for the inability of the proton precession gradiometer

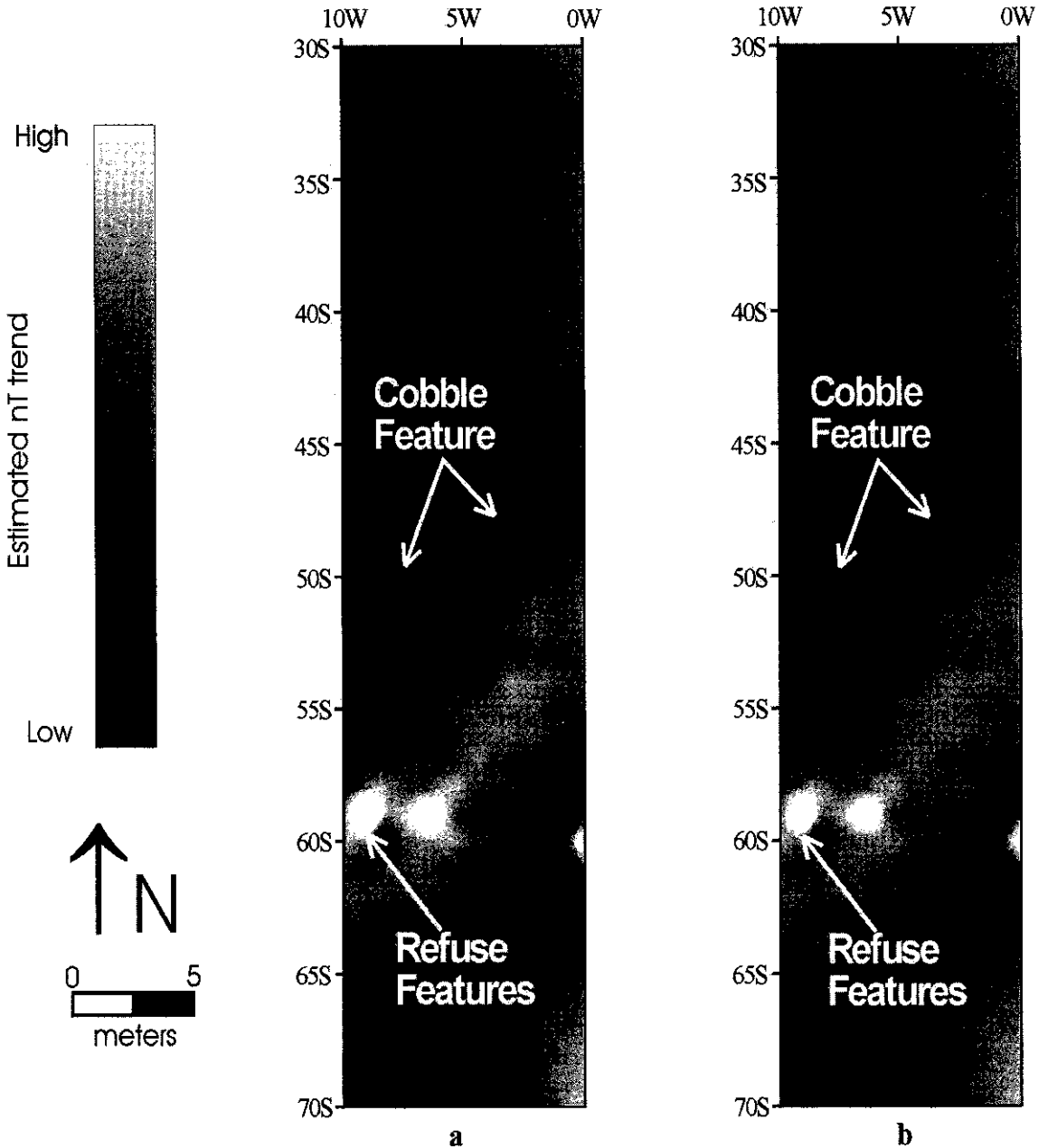


Figure 6. Comparison of diurnally-corrected alkali-vapor magnetometer images. The nT contour scale is only an estimated trend scale rather than an actual value scale, since the purpose is image comparison: *a*, alkali-vapor magnetometer at 0.85 m sensor height, corrected by proton precession magnetometer continuous basestation technique, 1 m line and 0.1 m in-line spacing, 0.5 nT contour interval, range of 50,240-50,370 nT; *b*, alkali-vapor magnetometer at 0.85 m sensor height, corrected by triggered basestation technique, 1 m line and 0.1 m in-line spacing, 0.5 nT contour interval, range of 50,270-50,390 nT. Note: A 53,000 nT standard was used to translate corrected basestation values to total field values. See the text for details.

to match the data from the alkali-vapor magnetometer sensor at 0.45 m height because the latter was 0.25 m closer still to the ground.

In addition, the separate data from the lower and upper sensors of the proton precession gradiometer offered further insights into the variable of sensor height. The resulting images displayed the same large magnetic features as did the proton precession gradiometer, but in only faint detail (Figures 5b, 5c). In other words, anomaly edge and definition were compromised, and they worsened with sensor height. The lower sensor of the proton precession magnetometer was situated about 0.7 m above the ground, but its results (Figure 5c) do not compare favorably with the total field alkali-vapor magnetometer survey at a 0.85 sensor height (Figure 4a). Even the results of the alkali-vapor gradiometer's upper sensor (Figure 4b), located 1.2 m above the ground, provided anomaly signatures only slightly less-defined than the lower sensor of the proton precession magnetometer (Figure 5c). This result is slightly counter-intuitive, but it indicates that instrument technology may prove to be a significant factor in the quality of magnetic data.

#### *Basestation Correction*

Finally, two different basestation correction procedures were employed on the total field alkali-vapor magnetometer survey to test their applicability and the effect of diurnal changes on rapidly-surveyed, small grids. The raw data image from the alkali-vapor magnetometer (Figure 4a) was slightly improved by the diurnal corrections available through the proton precession basestation (Figure 6a) and through the alkali-vapor magnetometer basestation triggered at 5-minute intervals during the survey (Figure 6b). The diurnally-corrected images are remarkably similar, and the ramifications for general magnetometer surveying will be considered below. It is noteworthy that the diurnal fluctuations recorded by both basestation techniques revealed a moderately quiet survey period, magnetically-speaking (Figure 7). The two graphs demonstrate the same upward trend of 2-4 nT during the 20 minute period, but their various points of non-correspondence suggest that the method is not foolproof.

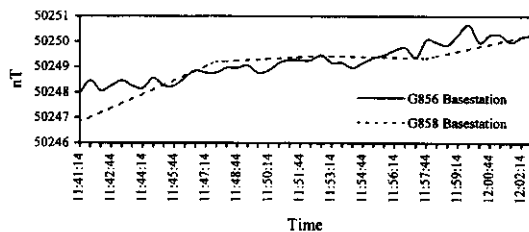


Figure 7. Comparison of diurnal graphs by different basestation techniques. The graph displays a comparison of the proton precession continuous basestation method and the alkali-vapor triggered basestation technique. The basestation location, thus initial reading, was different for the two methods.

#### Summary and Interpretation

The field tests and analysis of data detailed above raise three important considerations for magnetometer surveys in archaeology: (1) magnetometer type, (2) sensor configuration and height, and (3) diurnal corrections for single-sensor surveys. Ultimately, these three issues relate directly to the factors of data resolution, time, price, and labor input, and consequently, they impact archaeological research design. The different magnetometer options vary considerably along these lines, thus individual project choices will have to be made in light of particular research questions and goals.

#### *Magnetometer Type*

At least regarding the alkali-vapor and proton precession technologies, the new magnetometer types employing alkali-vapor sensors and/or continuous readings are the best field options available for archaeological survey. Our conclusions parallel those of Tite (1961:89), Ralph (1964:26), Larson and Ambos (1997:14), and Arnold et al. (1997:160). As demonstrated in this test case, the reasons for alkali-vapor model superiority are four-fold.

First, the speed of data acquisition is roughly six times faster with the alkali-vapor magnetometer and gradiometer than with the proton precession gradiometer. To complete the 10 x 40 m grid, the alkali-vapor model took 20 minutes, including basestation corrections every 5

minutes, while the proton precession gradiometer required 121 minutes. Moreover, for the large-scale initial magnetic survey, the ease of use precluded multiple small surveys of 10 x 10 m or 20 x 20 m blocks in favor of large blocks up to 40 x 100 m in size. For instance, the initial 8,000 m<sup>2</sup> survey area was surveyed in only four discrete blocks. Yet, to process these data in some software packages, survey blocks may have to be pared down to reduce the complexity of the contouring process, but this is an easier step in the laboratory than in the field.

Second, the alkali-vapor magnetometer not only can cover the survey area faster but also can generate ten times the readings of the proton precession magnetometer for the same survey grid. While the proton precession instrument sampled at stationary 1 m intervals with more than 5 seconds per sequential double-reading, the alkali-vapor instrument recorded 10 times per second. Even at 1 m/s pacing with the alkali-vapor model, this achieves a reading every 10 cm along the survey line. Archaeological features can often be small and discrete, thus this procedure insures that the magnetic anomaly will show up at more than one station, a necessary step in circumventing false positives (Weymouth 1986:350).

Third, the electronic console accompanying the alkali-vapor instrument is far superior to that provided with the proton precession gradiometer. The alkali-vapor instrument allows in-the-field editing of almost every aspect of magnetometer surveying so that potential problems or misinformation can be corrected before data are downloaded. Such a data collection method is essential for rapid surveying, and it is better suited for those not highly experienced in magnetometer surveys. This may be essential if the alkali-vapor machine is rented for a brief period during an archaeological project and must be returned before full-scale data processing has begun. In addition, the acquisition of data by the alkali-vapor instrument is perceptible through both visual and audible means, allowing the operator to monitor the subsurface features while surveying.

Fourth, the alkali-vapor magnetometer provides improved data clarity at sensor heights commensurate with the proton precession instrument. This variable can be considered in light of the 0.85 m height of the alkali-vapor magnetometer

and the 0.70 m height of the proton precession gradiometer's lower sensor provided in this study. More detailed comparisons are necessary, but the case presented here suggests that a single-sensor alkali-vapor instrument can provide slightly improved data at approximately 20% greater height in some cases. This is an interesting discovery, given that the other results were not unexpected in their correlation with sensor height (Table 1). The comparison of the alkali-vapor magnetometer sensor height of 1.2 m and the proton precession sensor height of 1.55 m, however, hints that the differences are negligible at this height.

The only noticeable disadvantage to the alkali-vapor magnetometer is the shoulder-strap for transporting the instrument. Not only is this a difficult array for maneuvering through or over tall vegetation while maintaining a constant operator pace, but also it produces measurement error. A recent study has shown that errors associated with translational and rotational sensor shifts relative to the console may be significant—up to one order-of-magnitude larger than the potential measurement error caused by instrument sensitivity—and that oscillations of the sensors left and right result in less amplitude variation than those movements up and down (Herwanger 1996). It has been suggested that these effects can be remedied through use of a mobile, non-magnetic cart with fixed sensor heights above the ground (Herwanger 1996:20).

Since a mobile cart would have variable utility on the variety of terrain surveyed by archaeologists, there is the popular option of a two-person recording system in which one surveyor carries the dual sensors mounted on a staff and the other surveyor transports the data collector. Although this configuration reduces the potential of recording error, it also drastically reduces survey speed and efficiency. Regardless of surveying choice, the possibility of experiencing nT fluctuations from sensor movement that are larger than the instrument's measurement sensitivity should warn archaeologists that they may not be measuring magnetic anomalies at the instrument's highest possible level of resolution.

#### *Sensor Configuration and Height*

More than simply field practicality, the true test for archaeological application is the quality

of the data. Test results suggest that the gradiometer arrangement, regardless of magnetometer sensor type, is generally superior to total field surveys for anomaly definition and placement, even with alkali-vapor instruments. As discussed above, this is in large part due to the upper sensor serving as a high-pass filter. Many field archaeologists often overlook this crucial distinction in archaeological applications. As several scholars have suggested, the gradient method excels in defining the spatial extent and character of relatively near-surface phenomena and for controlling magnetic disturbances of a diurnal or regional nature (Breiner 1973:49-50; Weymouth 1986:346-347; Clark 1996:67-78; Herwanger 1996:12). There is no question that the data generated by the alkali-vapor gradiometer excelled in all respects and is the instrument of choice of those tested here. As further support for the gradiometer configuration, although the proton precession gradiometer recorded data at a much slower rate and had a much larger in-line spacing, it displayed better anomaly resolution than that recorded by the faster, more sensitive alkali-vapor magnetometer with sensor heights greater than or equal to 0.85 m above the ground.

On the other hand, the technology available in the alkali-vapor magnetometer may outweigh the gradiometer necessity when compared to the proton precession model. This is most evident in the fact that the results of the G-856 Gradiometer compared poorly to the data recorded by the alkali-vapor gradiometer's lower sensor (i.e., equivalent to Magnetometer at sensor height of 0.45 m above the ground). The data presented in Figure 4 suggest that lowering the single sensor of the alkali-vapor magnetometer to approximately 0.5 m may provide good definition to features that are buried less than 1 m deep—the case at many historical sites—as long as the archaeological site is amenable to fine-grained magnetic prospection, void of high surface concentrations of iron debris, and surveyed on a magnetically quiet day. Unfortunately, these conditions are often hard to meet at historical sites.

In addition, given the alkali-vapor magnetometer's high-speed data acquisition, areas could be resurveyed with different sensor heights to achieve resolutions and coverage superior to that provided by the older-model proton

precession gradiometer. *An area could be resurveyed at least four times by the alkali-vapor magnetometer in the time required to conduct one proton precession gradiometer sweep of the area.* Importantly, it must be kept in mind that the high acquisition speed is dependent on the shoulder-strap design. As noted above, there is a trade-off between highly-efficient data gathering and potential distortion or masking of small-scale anomalies by sensor height shifts. The importance of these microscale features will vary by project and must be considered before beginning magnetic surveys.

If surveys are avoided between 10 A.M. and 2 P.M., when diurnal fluctuation can be the most pronounced (Breiner 1973:Figure 7), the comparability of the potential alkali-vapor magnetometer iterative surveys will be enhanced. For instance, in less than the time required for a proton-precession gradiometer to survey a grid at 1 m line and 1 m in-line spacing, the alkali-vapor magnetometer could survey the same area with (1) a survey of 0.25 m line and 0.05 m in-line spacing; (2) two distinct surveys of 0.5 m line and 0.05 m in-line spacing that ran first N-S, then E-W; or (3) two or more surveys at 0.5 m line and 0.05 m in-line spacing with the sensor at different heights. If nothing else, the speed of data acquisition in the alkali-vapor instrument make it possible for archaeologists to heed the recommendations to use a line spacing of 0.5 m (Sternberg 1987:371; Tabbagh et al. 1988:132; Clark 1996:81) to further refine archaeological magnetic data. As Scollar, Tabbagh, et al. (1990:472) state, "[t]he highest spatial frequencies are limited by the sampling interval of the line spacing, not the sampling along the line itself." The increase in sampling resolution will help mitigate problems of fluctuating sensor height as the magnetic anomalies have a better chance of being recorded accurately.

#### *Basestation Correction Procedures*

As for diurnal correction, two points are worth noting. First, both methods, the "continuous" proton precession stationary basestation and the "triggered" alkali-vapor magnetometer file-switching basestation, provided comparable correction for large-scale anomaly patterns and suggest interchangeability as long as intrareading intervals are small in the triggered mode. Given

the ease of this operation in the alkali-vapor magnetometer console, this may obviate the need for a separate magnetometer basestation, provided that sufficient "triggered" basestation readings are taken within the survey. The use of the alkali-vapor model eliminates the standard problem of triggered basestation readings requiring too much time (Farnsworth and Mueller 1992b:75). This method cannot control, however, for magnetic micropulsations of potentially high magnitude. As demonstrated in Figure 7, even a short survey duration can experience noticeable fluctuations that are not necessarily recorded similarly by different basestation techniques.

Second, the improvement of diurnally-corrected data over rapidly-acquired raw magnetometer data was only slight, but this situation hinged on the relatively quiet magnetic day experienced during the 1997 surveys. As would be expected, the continuous proton precession magnetometer basestation better monitored the subminute fluctuations, though they were small in size, than the discrete alkali-vapor magnetometer readings at 5-minute triggered intervals (Figure 7). Yet, if the anomalies of interest are less than 1-2 nT in contrast, the number of false positives (or negatives) will increase in proportion to the length of time between basestation readings. This is especially true in cases of high-amplitude micropulsations on the order of seconds (Breiner 1973:6). In fact, such rapid magnetic pulses of high magnitude would corrupt the proton precession gradiometer data since the instrument is not a true gradiometer because its sensors record sequentially rather than simultaneously. Such a problem may be more pronounced in areas with modern buildings or vehicular traffic, both concerns that plague many historical archaeologists' endeavors.

Certainly, high-resolution magnetometer work on many archaeological sites with extensive archaeological deposits is virtually impossible without ample basestation readings if a gradiometer is not used. For instance, the disturbance seen in the southern end of the 1996 alkali-vapor gradiometer surveys when the upper and lower sensors are viewed individually (Figures 4b, 4c) demonstrates the potential masking effect of magnetic fluctuations that may occur during survey and the ability of the gradiometer to correct these. For small surveys with expected large, high-contrast anomalies, however, a rapid

alkali-vapor magnetometer survey with no basestation corrections may be adequate when there are no serious magnetic disturbances from solar storms, power lines, and moving vehicles. The only problem may occur when piecing together adjacent small survey grids into a larger one because the smoothness of the edges may be compromised by diurnal fluctuations between surveys. In the end, since there is no way to ascertain that magnetic disturbances will be negligible during a given survey, a triggered basestation method, at minimum, is recommended for all magnetometer surveys.

### *Integrating Costs and Data Quality*

With these points in mind, a serious factor to consider in choosing and implementing a magnetometer survey is the research goal and the cost of magnetic surveying. These aspects are ones that truly resonate with the field decisions of archaeologists. Whether for purchase or rental, the magnetometer models considered here currently vary greatly in price, as our specific models will illustrate. According to a 1998 price list, a new proton precession gradiometer costs about \$6,800, an alkali-vapor magnetometer about \$16,000, and an alkali-vapor gradiometer around \$23,500. Rental charges, as compiled from several leasing companies, scale similarly with the proton magnetometer around \$15-33/day plus a \$66-95 mobilization fee, the alkali-vapor magnetometer around \$59-73/day plus a \$95-145 mobilization fee, and the alkali-vapor gradiometer around \$89-105/day plus a \$95-210 mobilization fee. An additional cost is that of operator labor. Any of the three instruments mentioned require the same number of crew members to move the survey lines, but only the alkali-vapor model can be run by a single operator if it is used in the shoulder-strap mode. The console and casing for the proton precession model must be kept away from the sensor staff, thus requiring a second operator to transport and control the data logger. This additional investment of person-hours may have considerable impacts on total project cost. If the alkali-vapor gradiometer sensors mount on a mobile vertical staff rather than the shoulder-carried rod, then all models require two operators and thus have equal labor costs. In addition, the labor cost of the alkali-vapor instrument will increase because survey



speed will diminish to levels commensurate with the proton precession instrument.

Weighed against monetary costs, the research questions of specific projects will guide appropriate selection of magnetometers. From a short-term perspective, involving the rental rather than purchase of these instruments, research odds are stacked in favor of the alkali-vapor models. Mobilization fees aside, an archaeologist can rent an alkali-vapor gradiometer rather than a proton precession gradiometer for about \$70 more per day. The alkali-vapor gradiometer can cover four to six times as much ground with one operator as the proton precession gradiometer can with two operators in the same amount of time, thus the cost difference is negligible, if not inverted, because the instrument would be needed for fewer days. The lower labor and time investment would quickly absorb the higher instrument rental cost. Similarly, the rental of an alkali-vapor magnetometer requires no more than \$40 extra per day than the proton precession gradiometer, and the potential iterative surveys involving tighter spatial sampling and multiple sensor heights will provide high-quality magnetometer data. Diurnal variations could be monitored with a proton precession magnetometer basestation, although the same financial outlay could rent a second alkali-vapor sensor.

From a long-term perspective, if high-resolution data are required for in-depth interpretations or for quantitative work, then a gradiometer is the instrument configuration of choice. The difference in purchase price in 1998 is almost \$17,000 between the proton precession gradiometer and the alkali-vapor gradiometer models; thus the choice of models is consequential. With an additional investment of less than \$10,000 above the proton precession gradiometer, the alkali-vapor magnetometer may perform equally, if not better than, the proton precession gradiometer through iterative and more spatially-intensive surveys. Overall, the alkali-vapor magnetometer is a high-performance option in terms of the speed of data acquisition, and the \$10,000 investment in the more advanced magnetometer technology is a worthwhile consideration. Common sense, however, indicates that one should rent the desired magnetometer for a few-day trial before purchasing or even renting it for long periods.

## Conclusions

In conclusion, there were five major points made regarding the two magnetometer models, three magnetometer surveys, and various survey parameters:

1. The newer models of alkali-vapor magnetometers, when used in gradiometer mode, outperform proton precession magnetometers, regardless of the position of sensors as long as they are fairly near the ground surface. The high performance is measured in terms of survey speed and efficiency, volume of data collected, temporal and spatial intensity of station readings, and sensor sensitivity.
2. Gradiometer modes, whether involving alkali-vapor or proton precession sensors, generate more refined data sets than total field magnetometer surveys. This is significant given the more advanced technology employed in optically-pumped single-sensor magnetometers. That is, our results suggest that the greater sensitivity of the cesium magnetometer may *not* produce inherently better data than the proton precession magnetometer in situations with *comparable survey intensity and sensor arrangement*. The cesium magnetometer's ability to acquire data at greater speeds and at variable sensor heights, however, offsets these results.
3. Sensor height is a key variable in the quality and type of magnetometer data. With little to no iron on the ground surface, relatively shallow archaeological depth, and a geomagnetically calm day, a low-sensor alkali-vapor magnetometer survey can produce data comparable, if not superior, to that possible with a proton precession gradiometer. In addition, a proton precession gradiometer and an alkali-vapor magnetometer with sensor height below 1.2 m outperform the proton precession magnetometer at sensor heights greater than or equal to 0.7 m.
4. Given the speed of data acquisition allowed in the alkali-vapor models through continuous gathering of data, the single-sensor cesium magnetometer can complete a given survey grid at four to six times the speed necessary for a proton-precession gradiometer. This factor renders cesium single-sensor configurations comparable, if not superior, to proton-precession gradiometer surveys by allowing more intensive

surveys of the same grid in the same amount of survey time.

5. Basestation correction procedures remain highly recommended components of magnetometer surveying, except when using gradiometers. The cesium magnetometer, however, can partially minimize the impact of diurnal or regional magnetic fluctuations through high-speed acquisition of data. Further control of magnetic disturbance can be achieved through triggered basestation readings, but this method leaves room for greater error when conducting long surveys and seeking small anomalies. Any decision to not use a separate basestation must always be informed by current geomagnetic conditions.

In the end, the choices of magnetometer type, configuration, and survey design are context-specific. For some cases, magnetometry for archaeological prospection at historical sites may not render accurate results regardless of instrument choice because of geological or modern cultural interference. In those cases where magnetometers are viable geophysical detection devices, however, the comparisons performed and the points made in this paper will serve as a preliminary guide to their use and selection by historical archaeologists. Although these results can serve as a guide for equipment selection and use, every archaeological context will require different survey methods, instrument types, and data reduction procedures.

As historical archaeologists continue to be called upon to investigate sites with geophysical techniques, these results may prove useful. Though beyond the scope of this paper, further avenues for advancing magnetometer survey should involve comparing these results to flux-gate gradiometer or Overhauser models, as others have begun to do (Smekalova and Bevan 1994; Clark 1996:174), integrating detailed quantitative analyses of anomaly signatures, and conducting more experimental and controlled replicative work (Martin et al. 1991) in magnetometer detection at historical and prehistoric sites. Finally, the technical and practical aspects have to be weighed against the rental or purchase cost of the instruments. There is no cookbook method for applying geophysical techniques to historical archaeology, but the continuous evaluation of various instruments and their implementation will permit more informed decisions by field archaeologists.

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