Geophysical Methods in Archaeology

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Introduction/Abstract

Non-destructive study of the near subsurface, depths of 100 m or less, has been of immense use to archaeologists since it was first used in the late 19th century. The cost in time and money as well as the inherent destruction involved with archaeological excavation can be minimized by judicious use of geophysical techniques. While these methods cannot yet resolve artifacts to a level necessary to replace excavation entirely, they can, if used properly, guide the archaeologist on where to dig. If the sought-after artifact is large enough or contrasts strongly enough with its surroundings geophysical surveys can provide considerable insight on the subsurface of the site even without follow-up excavation. One problem with the integration of geophysical methods with archaeology, however, is the complex physical and mathematical theory behind the methods. Geophysical experts spend years studying in order to use them efficiently and correctly in the field. While archaeologists utilizing these methods don’t need such an in-depth understanding of the theory behind them, a general idea of the physics allows for far more efficient use of these methods and in many cases can prevent over- or misinterpretation of data. The aim of this paper is therefore to describe and analyze the bases for and potentials of several major geophysical survey techniques presently used in archaeology.

History of Geophysical Prospection

To begin, the definitions of “geophysical” and “prospection” must be completely clear. For the purposes of this paper, geophysical properties are properties of subsurface material that can be detected and spatially distinguished using the techniques outlined in
this paper. Prospection refers to remotely observing the subsurface – that is, determining what lies below without actually seeing it.

Geophysical prospection is a focused area of study within the umbrella term “archaeometry” first coined by the Research Laboratory for Archaeology and the History of Art at Oxford University (Archaeometry online). The roots of systematic geophysical prospection can be traced back to a survey done by Lieutenant-General Augustus Pitt Rivers on Handley Down, Dorset, in 1893-5. He employed a technique known as ‘bowsing’ where a pick handle was beaten on the ground and differences in the sound produced indicated disturbances beneath the soil (Clark 1997). Colonel William Hawley’s survey of Stonehenge’s circular pits in 1921 took prospection even further towards identifying artifacts in the subsurface. Using an iron probe to test the density of the subsurface soil he was able to map out a series of circular pits around Stonehenge (Linford 2006). Another early method of geophysical study in archaeology involved analyzing aerial photographs of crops. Given that density and quality of crop growth are indirect observations of the depth and quality of the topsoil in which the crops are grown, any abrupt or systematic changes in depth or quality serve as significant indicators of buried evidence of human activity (Clark 1997). The expense of aerial surveys as well as the limited time window in which anomalies might be viewed, however, prompted a shift to increased investment in the development of ground-based direct-measurement techniques. Electrical resistivity techniques, developed for civil engineering, were first used for archaeological survey of Neolithic ditches dug into the bedrock near Dorchester-on-Thames by Richard Atkinson in 1946; by 1953 Atkinson had dedicated an entire chapter of his comprehensive Field Archaeology to the emerging technique (Clark 1997).
Other techniques began emerging rapidly within the next couple of years: by March of 1958 the first magnetic survey had been conducted. Development quickened with the introduction of more complex and efficient transistorized electronics. By 1966 research into electromagnetic methods had begun, leading to ground-penetrating radar (GPR) in 1975 and electromagnetic induction. Furthermore, the development of efficient data processing methods and algorithms allowed for increasingly widespread field use of geophysical techniques (Linford 2006). By 1984, Geoscan Research, the first company to make affordable geophysical equipment available to field archaeologists, was formed (Geoscan Research online). With the development of more complicated, delicate and precise survey techniques and the potential for gross misinterpretation of the data, however, geophysical prospection moved further into the realm of commercial providers who would work alongside archaeologists on a contract basis. By the late eighties the main geophysical techniques employed in archaeology today had already been introduced, but advances in digital computing and presentation of results continue to refine and improve the field.

**Potential Fields**

Potential field geophysical techniques are those that measure the variations within the earth’s potential fields, detected at the point at which the sensor is placed. The earth has associated fields, magnetic and gravitational being the primary ones used, which can be measured using geophysical equipment. Local abrupt variations within these fields, typically several orders of magnitude smaller than the strength of the fields themselves, can be detected and their position and strength used to identify possible artifacts. The main benefit of potential field techniques is that they sense constant or slowly changing
fields that require no applied energy. This allows for a faster sampling rate and less variables that the operator needs to control. The disadvantages are that the relative signal strength of anomalies related to the base field is incredibly small and requires extremely sensitive equipment, increasing the effects of outside noise on the final results. The potential field technique discussed in this paper will be magnetic surveying, the one that is most widely used in archaeology.

*Magnetic Geophysical Survey*

Ground-based magnetics is so widely used due to its propensity for finding most archaeologically significant items: kilned or fired clay (hearths, bricks, etc.), iron objects and pits and ditches all show up particularly well due to magnetic contrast with the surrounding field. There are several ways an object can become magnetized. For pits and ditches, the contrast in magnetic susceptibility between the fill and the surrounding subsoil causes the disruption. Baked dirt or clay, on the other hand, causes a disruption in the field because it has been essentially turned into a magnet by the heat of firing. Before firing magnetic grains within the clay are randomly aligned due to mixing. Once the clay is heated to above the Curie temperature (~700 C or more) the magnetic field “resets” and as the clay cools the magnetic minerals line up in the direction of the earth’s magnetic field, creating a weak permanent magnet (Renfrew and Bahn 2008). The same occurs for other materials, the strength of magnetization depending on the amount of magnetic minerals and the Curie temperature for the material. Decaying wood or other organic material can also cause preferential colonization of bacteria resulting in local biomineralization and weak magnetization (Fassbinder and Stanjek 1993). In addition to artifacts, structures tend to form highly significant anomalies in magnetic survey data.
They tend to be constructed of stone or some other dense material, whether natural or manufactured, which tends to contain a greater density of magnetic minerals than the surrounding lighter fill soil (Renfrew and Bahn 2008). Regardless of how the magnetization occurs, once the object is magnetized and moved out of alignment with the earth’s magnetic field it causes a disruption within the local magnetic field lines, which the magnetometer then measures.

There are various types of magnetometers available for use in the field, the main two used being flux-gate gradiometers and alkali-vapor magnetometers. Flux-gate gradiometers consist of two sensors arranged a set distance apart on a rigid vertical beam. The magnetic field gradient is calculated as the difference between the signals detected by each fluxgate sensor, automatically accounting for diurnal variations - natural daily fluctuations in the earth’s magnetic field - and minor tilt errors occurring if the system is not kept at a perfectly constant height and alignment. Each sensor consists of two high permeability cores, each with counter-wound wires carrying saturating AC current, which produce equal and opposite (canceling) magnetic fields (Fig. 1). When an external field is applied the net magnetization is no longer zero and a current is established in an amplified detection coil wrapped around both cores. The strength of the induced voltage is then proportional to the component of the external magnetic field parallel to the long axis of the cores (Clark

![Flux-gate Gradiometer design (Linford 2006)](image-url)
Because the earth’s magnetic field strength is on the order of ~50,000 nanoTesla (nT) and anomalies relating to archaeological artifacts are typically only 1-10 nT, incredibly sensitive instruments are necessary (Kirkendall and Crook 2009).

While the fluxgate gradiometers have enough resolution for many applications, a more recent development, the alkali-vapor magnetometer, is necessary to detect many weakly magnetic objects. The alkali-vapor system makes use of the unpaired outer electrons of the alkali vapor. Each atom in the vapor has a certain number of electron energy levels (for Cesium, the most commonly used alkali vapor, nine energy levels) each of which splits into three levels in the presence of an external magnetic field in a process known as Zeeman splitting. The energy difference across each split is in direct proportion to the strength of the applied field and once found can be used to find the total magnetic field. A light source (Cesium lamp) is shone through the vapor towards a photo detector. This lamp provides just enough energy for the electrons to occupy the original nine energy levels. Application of radio frequency energy through a coil wrapped around the vapor container allows the electrons to occupy the higher energy levels caused by the Zeeman splitting, clouding the gas and allowing less light through to the detector. Once a high enough frequency is applied the electrons occupy all of the split energy levels causing the vapor to become opaque and obscuring the detector. As soon as this happens the lamp shuts off and the vapor returns to its base state. The applied radio frequency is then used to calculate the energy of the split energy levels, which in turn is directly proportional to the total magnetic field (Kirkendall and Crook 2009). All that is needed to obtain the gradient as with the fluxgate system is to run two alkali-vapor sensors simultaneously and separated by some distance.
There are several advantages to using an alkali-vapor system over a fluxgate system. This process can be repeated every several nanoseconds, faster by several orders of magnitude than the flux-gate system. Also, such magnetometers have a potential sensitivity of ~0.01-0.001 nT, as opposed to the fluxgate system’s 0.1 nT (Linford 2006). However, alkali-vapor systems are also far more expensive, require more power to work and only measure the total field as a scalar quantity rather than a directional vector, as fluxgate systems do. Regardless, the cost of alkali-vapor systems is decreasing as they become more commonly used and for most archaeological applications all that is needed is the scalar quantity of the total magnetic field. The only real considerations between the two are therefore availability of the systems, access to sufficient electrical power in the field and necessary resolution of the survey.

Magnetic surveying is the most commonly used in archaeological investigations for several important reasons: versatility, sensitivity to many types of archaeologically significant artifacts and structures, simplicity and durability of the equipment, ease of use in the field and finally the ability to cover large areas in a relatively short period of time. As discussed earlier, items of archaeological interest tend to show up well in these surveys, including both artifacts and structures. Of course, natural formations of similar material might be mistaken for structures as well, but the ease with which a two-dimensional site map is constructed from gridded magnetic transects allows the archaeologist to focus on primarily those whose layout appears to be of human origin. Magnetic surveying equipment is also relatively simple to use, which means the surveyor needs less training than for other techniques. While interpretation of the data should normally be left to experts, at least the actual data acquisition can be undertaken with
minimal oversight, tying up less professional resources while in the field. Finally, the versatility of the magnetometer in the field has been a significant factor in its popularity. Magnetometers are carried above the ground, allowing for the survey of all but the roughest terrain. Soil conditions matter far less than they do for other systems and for a system integrated with an accurate GPS receiver even an exact grid is not necessary (although still recommended). Due to all of these factors, ground-based magnetic surveying has become the most commonly used geophysical tool for archaeological study. For finer resolution of anomalies including vertical resolution, however, one must look to other techniques.

**Applied Energy - Electromagnetics and Seismic**

The other main branch of energy-based geophysical prospecting relies on applied energies, typically in the form of waves (electromagnetic and seismic) or electrical current. Applied energy methods inject the source energy into the ground in whichever form required and measure the response, whether it’s direct, reflected, refracted or reradiated. The benefit to these systems is that resolution, depth of penetration and other factors influencing the results can be controlled, potentially yielding more detailed or specific responses than potential field data. The downside to these methods is that as the number of variables increases, so does the need for skilled operators as well as the possibility of misinterpretation. The applied energy methods to be discussed here include DC resistivity profiling and ground-penetrating radar (GPR).

**DC Resistivity/Earth Resistance Survey**

First used on a Neolithic site by Richard Atkinson in 1946, DC resistivity surveying (also known as earth resistance surveying) was the first geophysical technique
to produce systematic subsurface profiles of an archaeological site (Linford 2006). While
the methods have changed considerably since the first simple systems, the general idea is
the same. The essential principle is that the subsurface acts as a resistive electrical
conductor – when placed in series with
an electrical source through a positive
and negative electrode, current travels
through the ground and completes the
circuit (Fig. 2). In the simplified
model, if the current and voltage are
known the resistance due to the earth
can be calculated from the basic
equation $V = IR$: voltage = current $\times$
resistance (Linford 2006). In reality, the actual conducting material within the ground is mineral ions dissolved in groundwater forming a weak electrolyte. The measured resistance is therefore more a factor of local soil moisture concentration than geologic typologies, although the subsurface composition does affect readings: higher moisture content makes for lower resistance and higher resolution. This causes several problems with the simplified model. First, contact resistance between the highly conductive electrodes and the minimally conductive ground is so high that it eclipses any weak resistance anomalies from buried artifacts. In order to measure only the resistance due to subsurface variation two extra electrodes are added on the surface. These electrodes measure relative potential between their two positions rather than the absolute potential, thus accounting for resistances incurred at the electrodes and allowing for a number of different setups (Fig. 3). Second, polarization of the current electrodes can occur as dissolved ions migrate to the oppositely charged electrode. A simple solution to this problem is to provide an alternating current source, use non-polarizing electrodes (at

![Fig. 2 - Basic DC res. Circuit, solid lines are current, dashed equipotential (NGA online)](image1)

![Fig. 3 – Electrode arrays (USDOT online)](image2)
added expense) or statically discharge the electrodes frequently. One final correction that must be made to the simplified model is the distinction between resistance and resistivity. Measured resistance of an object relies on both the material properties and shape. When faced with finding differences in resistance within a bulk mass such as the subsurface, measurements must be made for incremental volumes; i.e., for a small portion of earth with cross-section dA, length dL and resistance R, a volume-specific property known as resistivity can be defined as \( \rho = R \times (dA/dL) \), measured in Ohm-meters (\( \Omega m \)).

Resistivity is essentially the representative resistance for a point source in the soil. Because the subsurface lacks homogeneity, an apparent resistivity representative of the entire path is calculated for a point in the subsurface. This resistivity is calculated from the measured resistance and the probable volume of earth that the current flows through, which varies with electrode array type and spacing (Linford 2006). At present, all DC resistivity surveys are done using multiple-electrode systems, typically with dozens of electrodes. This can produce hundreds of apparent resistivity readings for a single line within seconds or minutes, varying electrode spacing within the array in order to measure the resistivity at different depths for various positions along the line. These systems output data in a 2D depth profile showing apparent resistivity for the “slice” of ground beneath the line. Because each point is representative of the entire current path, however, these profiles look nothing like the actual subsurface makeup. Apparent resistivity profiles must then be changed to calculated resistivity models using iterative inversion techniques that essentially guess and check models that might produce the measured profile until a suitable match is found. These inversion techniques have been drawn up into computer programs that can be used as black-box resistivity calculators given the
data and parameters. However, it is necessary for any operator to know the process by which they arrive at the final result and recognize that it is merely a possible solution that happens to give the right apparent resistivity profile and is not necessarily (although it probably is) the correct result. Within these calculated resistivity profiles it is then possible to see anomalies that correspond to contrasts in resistivity, which could indicate anything from human activity to a tree’s root system or large rock (Kirkendall and Crook 2009). Successful interpretation of DC resistivity data typically requires a skilled and experienced operator. To optimize the results, different arrays or setups of electrodes can be used (Fig. 3). Each array has its own advantages and disadvantages as to what types of artifacts it can resolve, but the following is generally true: the Wenner and Schlumberger arrays are better suited for sensing horizontal structures because they are more sensitive to vertical variations in resistivity, the dipole-dipole* and pole-dipole arrays are more suited to finding vertical structures such as buried walls because of their sensitivity to horizontal changes in resistivity. The sensitivity of each array for certain variations is due to the differences in separation between current and potential electrode pairs as well as other factors. As with interpretation of the results, it is typically best to have an experienced operator decide on the optimal array type for the conditions before heading out into the field. This is done using forward modeling where the operator creates a diagram of the expected subsurface profile in the computer. The program then returns what the results from the expected profile would look like and once multiple array types are tested this way, the results are compared and the array type that produces the most similar profile to the input is chosen. As with all geophysical methods this requires

* A “pole” is a single polarized electrode. A “dipole” is a set of two oppositely-charged poles (+ and - current electrodes, for instance).
some prior knowledge of the site, specifically in terms of resistivites and depths for both the soils and expected artifacts.

Earth resistance survey was the very first of the modern geophysical techniques to be applied to archaeology. This method works extremely well under optimal conditions and can provide remarkably accurate spatial and geophysical data on items of archaeological interest; however, as conditions move farther from optimal, the usefulness of this survey method becomes severely limited. In order for this method to work there must be sufficient moisture in the ground to carry the current from one electrode to the other. Without sufficient moisture, in dry sand for instance, the resistance of the earth is so high that even if some of the current were to complete the circuit any archaeological artifacts would be obscured by the noise. Furthermore, there must be sufficient contrast between the resistivity of the earth and that of the artifact. This contrast is caused by the properties of the two materials – high resistance anomalies would be expected from non-porous artifacts or structures or even air pockets, while low-resistance anomalies come from more moisture-retentive artifacts such as filled ditches or concentrated deposits of decaying organic material (Linford 2006). Of course, if the resistivity of the subsurface matrix that the artifact is buried in is similar to that of the artifact then there is no contrast and no anomaly in the data. This technique works well for a fairly wide range of conditions, the best being clayey soils with high-resistivity artifacts. However, if working in drier areas, ground-penetrating radar is usually a better option.

*Ground-Penetrating Radar (GPR) Survey*

GPR, in its most general sense, can be defined as any method utilizing non-inductive propagation of radio-frequency electromagnetic radiation to image structures.
The technique was initially developed by civil engineers to evaluate the internal integrity of structures but the potential for archaeological study has led to its rapidly increasing use in the field. As the most recently developed method, GPR surveying typically requires skilled operators although the development of continuous-feed devices and simplified interfaces has led to much greater ease of use in recent years.

GPR systems transmit impulses of electromagnetic (EM) energy into the ground in the form of waves from a source antenna on the surface, typically with a frequency in the range of 20 to 1000 MHz, depending on the desired depth of penetration and resolution. This wave then travels through the ground until it encounters an object of contrasting conductivity ($\sigma$) or relative dielectric permittivity ($\varepsilon$) to the bulk subsurface medium. Contrast in magnetic permeability ($\mu$) also affects results, but in most sites is negligible. If the contrast is in dielectric permittivity, then the object absorbs some or all of the magnetic and electric energy of the EM wave depending on the level of contrast, forming weak electrical eddy currents within the object itself. The energy from these eddy currents is then reradiated from the object in the form of weak EM waves which are then picked up by a receiver antenna on the surface and converted back to electrical current. The strength and time delay of the response can be used to determine the depth of the buried object. Typically, archaeological materials are semi-transparent to GPR-frequency EM waves, leading to multiple responses at differing time delays from a single impulse (Conyers 2004). A common analogy used to describe GPR is marine-echo sounding, where the distance to certain objects can be distinguished from time delay and amplitude of the response, although in the case of GPR it is reradiated energy rather than simple reflection.
Depth of penetration of GPR systems can vary greatly with conditions and settings; typically, the larger the frequency used and the lower the conductivity of the ground, the deeper the signal goes. This is because large frequency waves have a much lower resolution due to their long wavelengths, so less energy is bled off (attenuated) by reradiating responses. Low conductivity of the soil means that the soil itself doesn’t draw off as much of the electromagnetic energy, allowing the wave to travel further before it dissipates to the point of negligible response strengths. Conversely, the higher the conductivity the less distance the wave can travel before disappearing (Dolphin 1997). A common method for rough estimation of GPR penetration depth in meters at common frequencies is depth = 35/σ, where σ is the conductivity of the soil in milliSiemens/meter (mS/m). The conductivity of soil in these units is typically a value between 5 and 100 and should be found using geological estimates of the soil type before the survey is begun.

As opposed to earth resistance surveys, therefore, GPR does better in drier, less conductive (more resistive) conditions. When working in sandy or dry desert environments this technique works very well; once the soil becomes wetter, however, the energy sapped by the surrounding soil limits its effectiveness. Moreover, the seemingly simple solution of increasing the energy of the EM impulse will necessarily raise the frequency, cutting down on resolution (Kirkendall and Crook 2009). GPR is best used over dry soil environments or over non-porous solid rock, concrete or similar material that holds minimal moisture.

GPR results in 2D depth profile form are typically difficult to read and interpret, requiring an expert to do so with a reasonable degree of accuracy. Artifact anomalies do
not show up as recognizable shapes but rather as hyperbolic response curves centered over the position of the artifact, similar to non-inverted DC resistivity data. As with most other geophysical surveys, GPR data can be shown as a site map using interpolated values from a gridded series of profile transects. This format loses indication of depth but shows more of an overall picture than simple 2D profiles. One major current area of research in GPR application is of fully 3D models of sites using densely gridded transects. With the development of ever-simpler GPR equipment, the speed with which surveys can be made is approaching the point where running a sufficient number of lines to create a fully 3D model with minimal interpolation is no longer prohibitively time-consuming and expensive.

**Other New and Lesser-used Methods**

The following section describes methods that are used less whether because of limited scope, cost, difficulty or simply because they’re newly developed. Only the most common or those with the most potential have been mentioned here due to space constraints.

Capacitative arrays work on a similar basic circuit principle to DC resistivity arrays but aim to speed up the process by creating currents within the ground without actually inserting electrodes. Theoretically, actual contact between the electrodes and the ground would be replaced by capacitative coupling where an alternating current in the electrodes, when placed on an insulating mat, would charge the electrode and cause an equal and reverse potential within the ground. This would allow earth resistance surveys to proceed at a much higher speed because there would no longer be a needed to statically insert electrodes into the ground; rather, the whole system could be dragged along at
similar rates to GPR or magnetic surveys (Linford 2006). Currently, these systems have only been successfully conducted for large-scale, deep penetration without the resolution necessary for most archaeological surveys, although continued research may make this method viable for archaeological study.

Geochemical methods have been used in archaeological study for a long time, the most common example being soil phosphorus detection. This method is limited in scope due to sample collection rates, sample analysis expense and the length of time required to return significant results. This method can be very helpful for testing hypotheses on ancient uses of various predetermined sections of sites but is of less use when completely surveying a site.

Borehole (vertical) systems have been developed for many geophysical survey systems, the major one being the borehole version of an earth resistance survey known as electrical resistance tomography (ERT). These systems can provide much more detailed vertical profiles than surface surveys, but suffer from the major disadvantage that a set of highly destructive and invasive boreholes must be drilled into the site, possibly damaging the remains.

Finally, SQUID magnetometers (super conducting quantum interference devices) have been tested in the lab to have a resolution of .00002 nT, about 200 times that of alkali-vapor sensors and several thousand times better than flux-gate systems. These systems have been found to be very impractical in the field, however, due to the very low temperatures required (Chwala et al 2001).
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