Archaeological Magnetic Surveying

UPII Honor’s Paper

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"Like an iceberg, only a small fragment of a country's archaeology is visible above the surface; the rest is buried by gradual accretion of soil to depths varying between tens of feet and a few inches. Even in the latter case there is often no surface indication until digging throws up pottery fragments." Professor M.J. Aitken of Oxford University wrote this in 1961 in his book Physics and Archaeology. Aitken is known for being one of the first researchers to incorporate magnetic methods into the field of archaeology in the 1950s.

The classical archaeological method of surveying land by trenching with trowels and brushes can be a timely process, not to mention it can damage a historical site. However, scientific methods based in physics, allow archaeologists to understand what's hidden below the surface before ever breaking ground.

Modern archeologists use geophysical prospecting to search for and characterize historical sites. Archaeological remote sensing (also known as archeogeophysics) helps archaeologists to see features buried beneath Earth's surface, such as buildings, walls, streets, and ditches (National Park Service 2011).

There are numerous methods of remote sensing used to suit the topography, climate, and social considerations of a historical site; this paper describes how measuring the Earth's magnetic field can be used to survey a historical site for archaeological structures.

Magnetic surveying (also called magnetic prospecting) involves an archaeologist using a magnetometer to measure the Earth's magnetic field over a plot of land. Incongruities in the survey may reveal underground objects that are known to affect the magnetic field for various reasons.

Due to currents in its molten core, Earth’s surface is surrounded by a magnetic field. The Earth can be modeled as a large bar magnet with a north pole and south pole and magnetic field lines circling the earth, the way dipole field lines extend from a bar magnet. Earth’s magnetic south pole is located near it’s physical north pole, though the poles do not coincide exactly. The magnetic axis deviates slightly from the geographic axis (the axis of rotation). This vertical deviation is called the magnetic declination or magnetic variation. The magnetic field also deviates horizontally. At most locations on the Earth’s surface, the magnetic field is angled up or down; this angling is called magnetic inclination. (Young and Freedman 2012)

Earth’s magnetic field also differs in magnitude, depending on surface location. It ranges between about 35,000 nT to 70,000 nT (Near Eastern Archaeology 2006). Past human activity can, however, cause disturbances in the magnitude of the magnetic field.

These disturbances can be measured today using sensitive magnetometers. Some magnetometers measure only the strength of the magnetic field, while others measure strength and direction; the latter type is called a vector magnetometer.

A fluxgate magnetometer is a kind of vector magnetometer that was invented by Victor Vacquier in 1940. In WWII, the fluxgate magnetometer was attached to a blimp, and later to low-flying airplanes to detect large objects made of ferrous materials, such as submarines. (www.earthsci.unimelb.edu.au 2012).

The fluxgate magnetometer consists of a ferromagnetic core wound with a drive coil (also called an excitation or winding coil) and a pick-up coil (also called a sense coil). The physical arrangement and geometry of the core differs between designs.

An AC current is applied to the drive coil. When the current is applied in one direction, it causes the ferromagnetic core to become magnetically saturated. Reversing the direction of the current causes negative saturation. Since the magnetic field repeatedly changes direction, the second coil experiences a change in magnetic flux. An electromotive force acts to resist the change in induced current, so an induced voltage is observed between the ends of the second coil (see Figure 1 in Appendix).

If no external field were present, the magnetic flux through the core would only depend on the magnetic field created by the drive coil. However, when the ferromagnetic core is in the presence of an external field, the induced voltage in the pick-up coil is affected. The component of the external field that points in the same direction as the core will increase or decrease the time it takes the core to become saturated. The amount that the saturation curve shifts is detected, and then the external magnetic flux density is derived.

Since the user only cares about detecting the external magnetic field, the fluxgate magnetometer can be designed so that the magnetic field generated by the drive coil does not create a signal in the device. To do this, an additional core is aligned parallel to the first one, and the drive coil around the second core is connected in series with the drive coil around the first core. This creates equal and opposite magnetic fields in the two cores. The pick-up coil is wrapped around both cores, so that the net magnetic flux through the pick-up coil is zero, resulting in zero induced voltage (see Figure 2 in the Appendix).

When an external magnetic field is present, the two cores will respond differently to the field (because their magnetic fields are in opposite directions), and the pick-up coil will experience different shifts in the magnetic flux of each core (see Figure 3 in the Appendix).

The voltage induced in the pick-up coil can be calculated by:

$$V = na\frac{dB}{dt}$$

Where n is the number of loops of the pick-up coil, a is the cross-sectional area of the coil, and B is proportional to the external field (Forslund 2006).

The fluxgate magnetometer can be taken one step further and be assembled in a gradiometer configuration, which measures the gradient of earth's magnetic field. In the absence of archaeological and geological anomalies, Earth's magnetic field is uniform over a particular location on the its surface. When there are such anomalies, the field is not uniform. By spacing two magnetometers a distance apart in the vertical or horizontal direction, they can measure a gradient in the field, and therefore, identify that there is a near-surface disturbance in Earth's magnetic field. Gradient magnetic field surveys measure this derivation from the uniform field strength, and report a positive derivation if the magnetic field was increased, or negative if the field was decreased (www.alphageofisica.com.br 2005).

Magnetometers are used to detect the following kind of archaeological remains:

- Objects made of iron.
- Structures which once were used for fires, such as kilns, ovens, furnaces, and hearths.
- Ditches filled with soil or garbage.
- Structural foundations, walls, roads, and burial tombs.

Using magnetometers to uncover iron objects is the most obvious application of this instrument because iron is highly ferromagnetic. Even in the late 1800's, Sweden used magnetic measurements for geological prospecting of iron ore deposits. Using magnetic methods to detect iron objects of archaeological importance, though, is rare (Aitken, 1960).

Kilns, roads, and buried ditches do not possess the same magnetic properties that iron objects do. To detect these kinds of formations, magnetometers are required to be very sensitive to changes in the external magnetic field; they can detect variances of 0.1 nT, so they are excellent at detecting subsurface anomalies that cause even faint disturbances in Earth's magnetic field (Near Eastern Archaeology 2006).

Firing structures such as kilns and ovens can be described by their thermo-remnant magnetism, which is a permanent magnetism that results after certain materials are heated to a high temperature. Civilizations from around the world have used kilns for tasks such as pottery making, and even though they vary in design, they are all made of out of clay. Like most soil, clay contains significant amounts of the iron oxides, such as magnetite. Each grain of the iron oxide has a magnetic domain that points in a random direction, so that their magnetic domains effectively cancel each other out. When the grains in the clay are heated, some of the domains line-up with Earth's magnetic field. After the heat is removed, domains remain aligned, and their magnitudes add together to create a net magnetism. The maximum remnant magnetism results after clay has been heated to a dull red heat (about 700°C), though any amount of heat will cause permanent magnetization (Brothwell 1970). This remnant magnetism differs from the surrounding soil, and can be detected by magnetometers.

Detecting pottery kilns is important to archaeology because pottery fragments are often the most significant indication about a site's history. Pottery fragments are durable and common remnants that can be used to date a site. If the same pottery is found in two locations, a link between those locations can be formulated. A pottery kiln provides information about the geographical and time origin of the pottery, and may even contain complete pieces of pottery to study (Aiken 1961).

Ditches and trenches can be detected because their magnetic susceptibility differs from the surrounding soil. Magnetic susceptibility describes the proportionality between the applied magnetic field on a material and the magnetization of the material. If a material has a high magnetic susceptibility, the magnetic field is increased; if it is low, the magnetic field is decreased. Ditches and trenches usually have a higher susceptibility because they have a high degree of top-soil, which has built up over the years. Ditches that have been filled with decaying organic matter have a stronger magnetic presence because iron within the soil is altered by organic decay.

Unless walls are built out of brick or volcanic rock, then they have a negligible magnetic property. However, they can still be detected for the opposite reason that ditches are detected. Walls are detected because of an absence of top soil compared to the surrounding ground. Even though walls may only cause a faint magnetic disturbance, they are easy to detect because of their linear disturbance pattern (Aitken 1961).

The pattern caused by magnetic anomalies are dectected when archaeologists conduct a magnetic surevey over a set area of land. Archaeologists carry a magnetometer in a grid formation to collect data. Data is then processed with software provided by the instrument's manufacturer. After the data is cleaned up with various algorithms and filters, a map of the plotted grid is produced. The map will show regions of increased magnetic field (due to remnant magnetization or increased soil susceptibility) and decreased magnetic field (due to remnant magnetization in the opposite direction of Earth's field or decreased soil susceptibility) (Archaeo-Physics 2012).

There are drawbacks, however, to magnetic surveying. Any irrelevant iron, such as horseshoes and wire fencing, distorts a survey. So, magnetic surveying is more effective in remote locations where modern human habitation doesn't interfere with readings (Aiken 1961).

Magnetic methods have been successfully used in many archaeological discoveries. Recently, magnetic methods were used in Dahshour (or Dashur), Egypt, which is located 30 km south-west of Cairo. Though less famous than the neighboring pyramids of Giza, Dahshour contains momentous pyramids including the white pyramid of Amenemhat II, the black pyramid of Amenemhat III, the red and bent pyramids of Snofru, and the pyramid of Senustret III. Also present are monuments related to each pyramid, such as mortuary temples and auxiliary tombs for family and officials.

A team of researchers used magnetic surveying to discover outbuildings of the white pyramid of Amenemhat II. They used a vertical fluxgate gradiometer to survey 68,000 m^2 on the eastern side of the pyramid. After processing the data, they were able to plot a map of the gradiometer data and detect magnetic anomalies (see Figure 4 in the Appendix). Based on their knowledge of Egyptian life, the researchers were able to understand the significance of these anomalies and plan for their careful excavation. The discovered structures included a causeway (which is a linear structure ancient Egyptians used for funerals) and a mortuary temple, which are both made out of mud bricks (see Figure 5 and Figure 6). Ancient Egyptians used mud bricks to construct bases of pyramids, tombs, houses, and fortresses. The mud comes from the Nile River and is composed of clay and sand, which contain magnetic grains detectable by a magnetic survey (Abdallatif 2010).

In this example of archaeological research, magnetic prospecting helped researchers to not only discover ancient buildings, but to do so in an efficient and preservative manner. It is also an example of how physics can be used to learn about the past and preserve cultural heritage sites. With continued incorporation of physics into archaeology, excavations can continue to become more efficient and fruitful.

Appendix

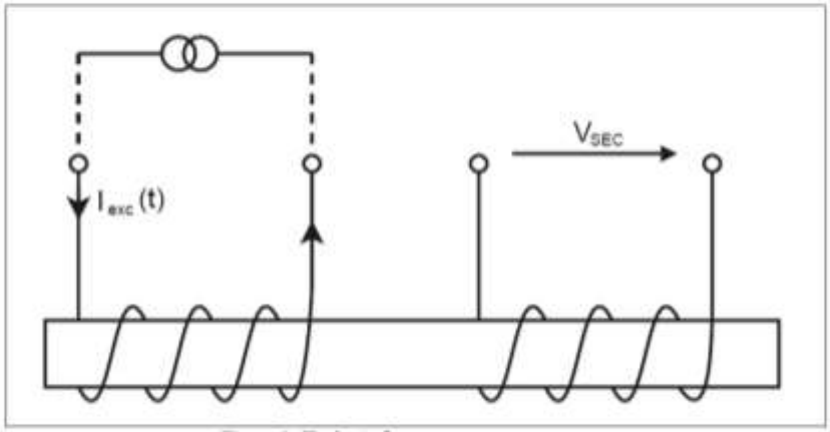

Figure 1: *Basic fluxgate magnetometer sensor (Forslund 2006).*

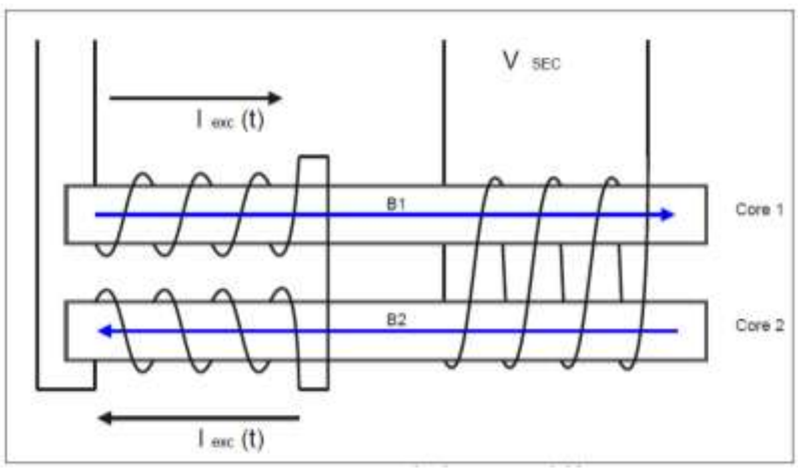

Figure 2: *Design to eliminate net voltage induced by drive coil (Forslund 2006).*

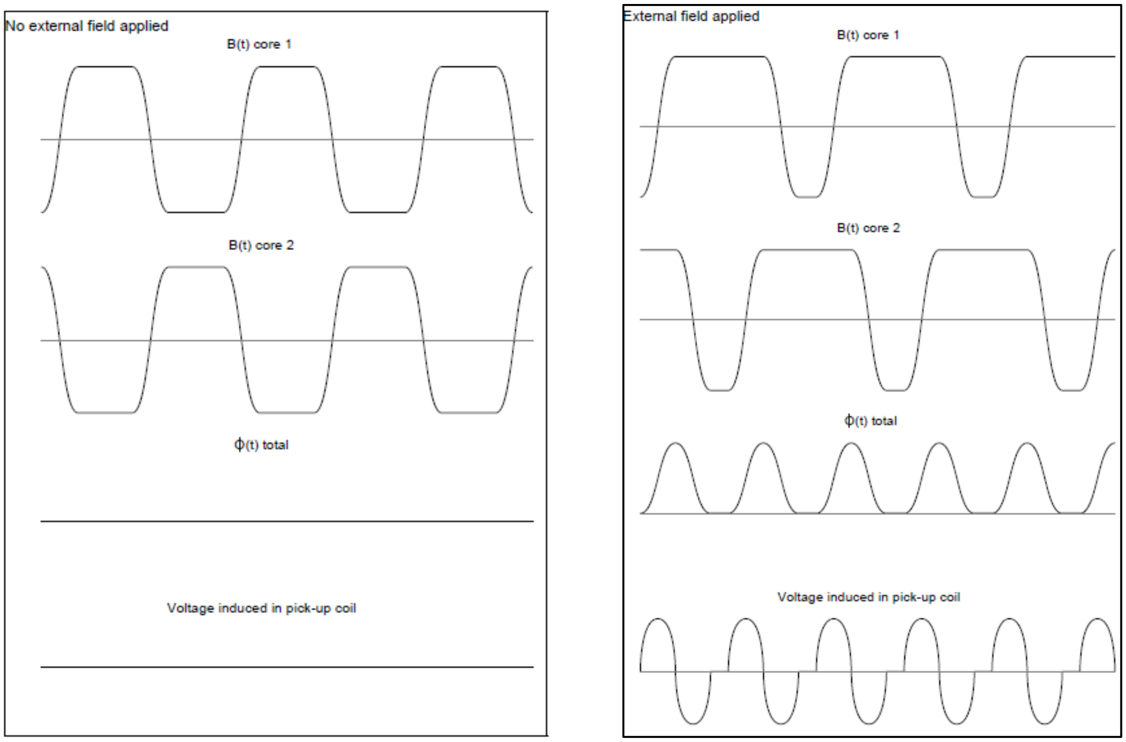

***Figure 3**: Magnetic flux and voltage readings in no external field versus readings in an applied external field (Forslund 2006).*

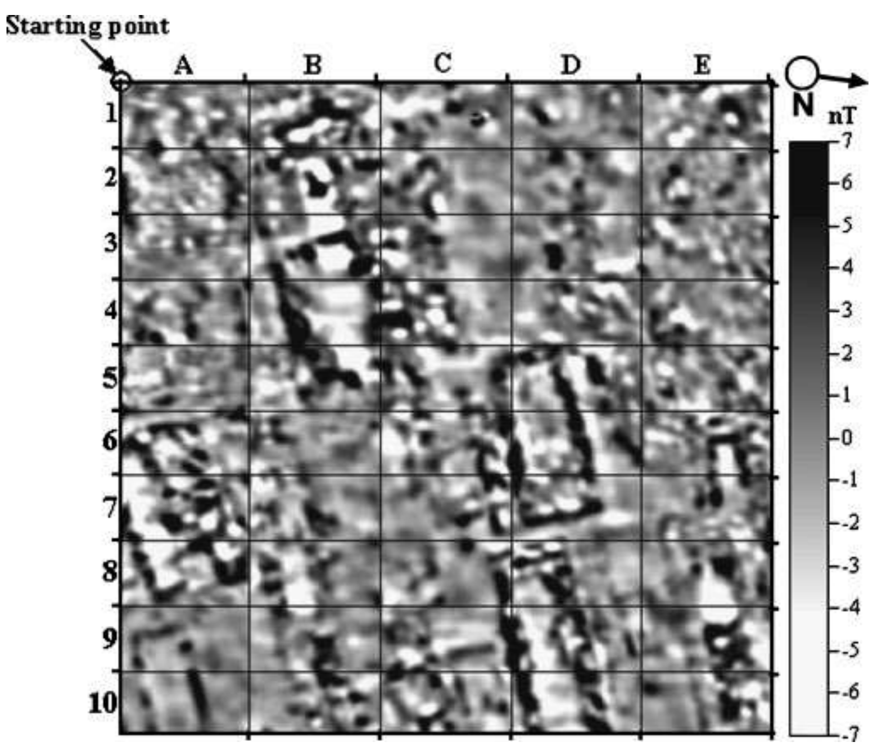

***Figure 4:** Magnetic image of the outbuildings of the white pyramid of Amenemhat II (Abdallatif 2010).*

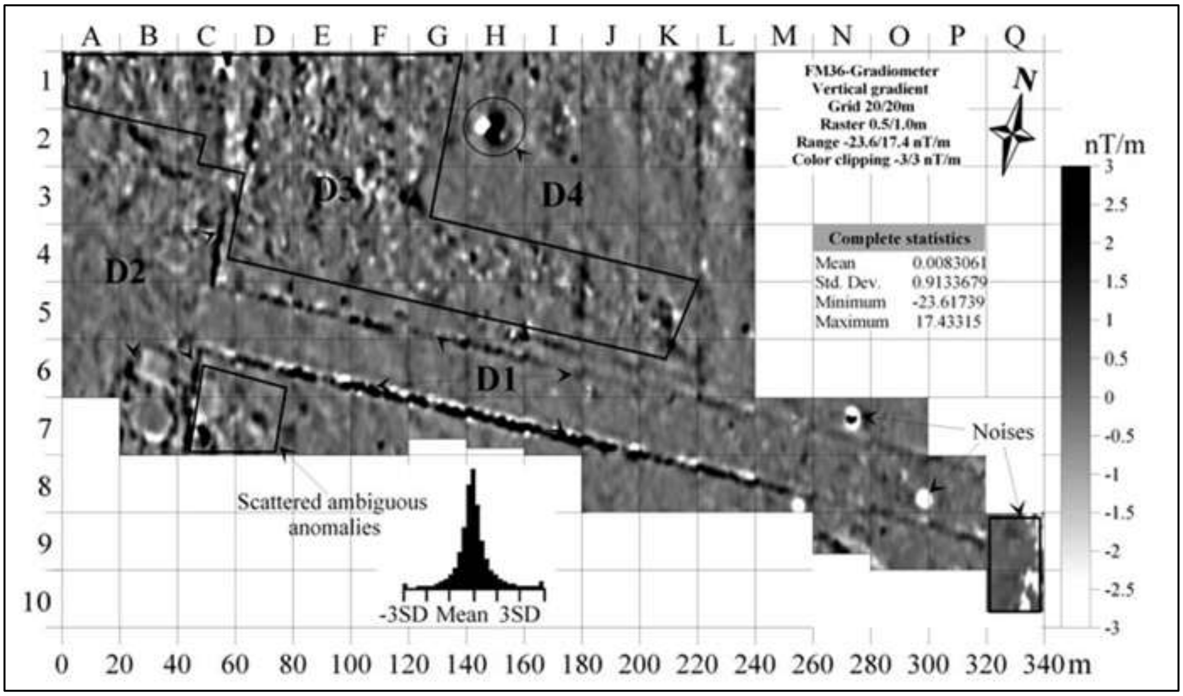

***Figure 5:** Magnetic image of the causeway and mortuary temple of the white pyramid of Amenemhat II (Abdallatif 2010).*

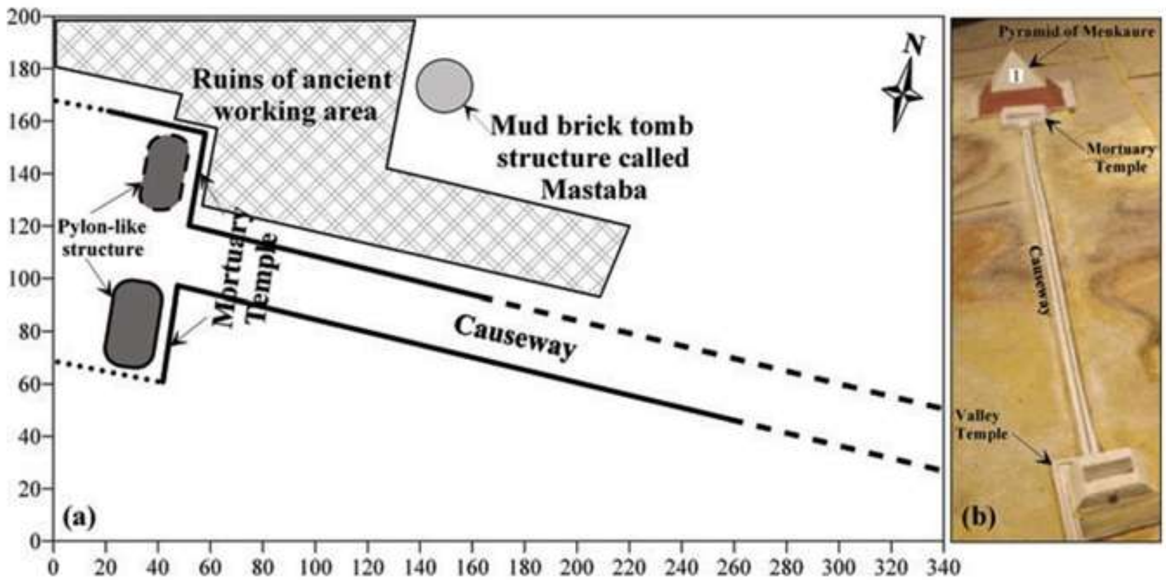

***Figure 6:** **(a)** Drawing of the causeway and mortuary temple of the white pyramid of Amenemhat II. **(b)** The discovery is expected to resemble the construction of the pyramid of Menkaure at Giza (Abdallatif 2010).*

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