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Title: Identification of shapes and uses of past landscapes through EMI survey

Authors: François-Xavier Simon and Ian Moffat

Over the last ten years, the use of Electro-Magnetic Induction (EMI) instruments for archaeological purposes has increased considerably. This development has come both from the availability of new instruments' with multi-coils spacing allowing a multi-depth analysis and because of the wide availability of high quality GPS positing which can be easily integrated with EMI. These new possibilities promote the use of EMI instruments for the study of archaeological landscapes and sites. Indeed, the capability to simultaneously map both the electrical conductivity and the magnetic susceptibility presents a great advantage for archaeological purposes compared to other geophysical instruments. The combination of these two measurements means that it is possible to geomorphologically characterize past landscapes while simultaneously mapping anthropogenic activities. To maximize the potential of EMI measurements, this technique requires specialized processing and calibration to limit confusing and unclear results. In order to obtain quantitative conductivity and magnetic susceptibility data, it is necessary to correct instrumental drift and calibrate for local soil conditions. In this paper we introduce the theoretical basis of the EMI technique, discuss common instruments and explain the calibration procedure before presenting three case studies that illustrate applications of EMI to archaeological sites on a range of scales.

Introduction

The current use of EMI techniques in archaeology is inherited from a long story of discovery and improvement. The first case studies of this method for archaeological applications was undertaken in the 1960s to map the soil conductivity at a proto-historic site in southern England (Howell 1966). On subsequent surveys, it was demonstrated that EMI can be sensitive to the magnetic properties of soil through the use of both a TDEM (Time Domain Electro-Magnetic) instrument (Colani and Aitken 1966) and a FDEM (Frequency Domain Electro-Magnetic) instrument (Tite and Mullins 1969). Furthermore, it was shown that FDEM instruments can

simultaneously measure both electrical conductivity and magnetic susceptibility (Parchas and Tabbagh 1978). A range of instruments were then built and tested during the 1970s and the 1980s (McNeill 1980; Tabbagh 1986). Since it is not necessary to have direct around contact for measurements, EMI is a well-adapted method often used to map the electrical conductivity over large areas, where electrical measurements would need more time for acquisition. The most common contemporary use of EMI is mapping the electrical conductivity of soils, which fails to exploit the potential of this method. New approaches include the robust calculation of magnetic susceptibility (Martnet 2000) and the use of multi-coil instrument for the simultaneous measurement of multiple depths (De Smedt et al. 2013).

Theory

EM measurement is based on the transmission of a time varying magnetic field (primary field) through the transmitting coil (Fig. 1). This field spreads in the soil and creates eddy currents in conductive materials. Currents generate a new electromagnetic field called a secondary field. Both primary and secondary fields are then measured by the receiving coils. At the same time, the electromagnetic field magnetizes the soil through an induced magnetization. This magnetization also modifies the secondary field. The intensity of this magnetization of the soil is magnetic susceptibility. The primary and the secondary fields are offset in time. It is then possible by the identification of both parts of the complex electromagnetic secondary field to characterize both the electrical conductivity and the magnetic susceptibility.

Figure 1: Principle of electromagnetic measurement

The behavior of electromagnetic fields is described through Maxwell's equation. Three physical properties are involved: the electrical conductivity, the dielectric permittivity and the magnetic permeability. The use of approximations allows the simplification of Maxwell's equation and offers a mathematical solution to understand the EM signal (Scollar et al. 1990).

At first, the magnetic permeability of natural material is very low (close to μ_0). Moreover, in the case of the low frequency (<100 kHz) instrument, the displacement current is negligible compared to the conduction current. In this case, only the electrical conductivity and magnetic permeability affect the EM field. This approximation is known as the induction case where the conductivity needs to be high enough to verify that:

$$\sigma > \epsilon \omega$$

In a low frequency case, Maxwell's equations are reduced to:

$$\nabla^2 E - \sigma \mu \frac{\partial E}{\partial t} = 0$$

$$\nabla^2 H - \sigma \mu \frac{\partial H}{\partial t} = 0$$

Induction currents are then concentrated close to the surface. limiting the depth of investigation. To describe this effect, called the skin effect, the following parameter is employed:

$$p = \sqrt{\frac{2}{\sigma \mu \omega}}$$

$$\text{with } \omega = 2\pi f.$$

The skin depth or penetration depth, p, is defined as a diminution of the amplitude field to 1/e of its initial amplitude. This value limits the effective investigation depth.

In the general FDEM case, the electrical conductivity mostly affects the response of the EM signal. Nevertheless, in the case of a Low Induction Number (LEN), the response of the conductivity is completely related to the quadrature out-of-phase part of the signal so the in-phase part is related to the magnetic susceptibility. The low induction number is defined by the following approximation:

$$L^2 \sigma \mu \frac{\partial}{\partial t} \ll 1$$

where L is a characteristic size of the system (depth and size of the target, coils spacing). If $L < p$, we are close to the static case and the depth of investigation is controlled by L. If $p < L$ then the depth of investigation is controlled by the frequency through the penetration depth.

Wait/McNeil approximation

Considering the case of a Low Induction Number and a low frequency. we can apply the following relation linking the ratio of primary and secondary field with the electrical

conductivity (Mc Neill 1980). This equation is available for the electrical conductivity and limited to some specific cases:

$$\frac{H_s}{H_p} \cong \frac{i\omega\mu_0\sigma s^2}{4}$$

Where, $\omega = 2\pi f$, f = frequency, H_s secondary field, H_p primary field, σ the ground conductivity and s the inter-coils spacing. As an example for a high apparent conductivity, this relation however is not completely true.

The full solution

In the absence of approximation, the in-phase is not fully related to the magnetic susceptibility nor is the quadrature fully related to the apparent conductivity. The in-phase component can be affected by the apparent electrical conductivity (for high value of conductivity) and quadrature out-of-phase can be affected by the quadrature component of the magnetic susceptibility. The use of a full solution avoids these limitations. The calculation of the response of a homogeneous ground, or of layered one, has been established by the work of Wait (1959) and is based on Hankers transforms. It can be rapidly calculated using convolution products (Guptasarma and Singh 1997). Complete expressions and a description of the different subsequent approximations can be found in Thiesson et al. (2014). They express the measurement in terms of apparent conductivity and susceptibility, based on a simplified conversion since the variations are monotonous yet not simply linear. In this case we overpass the problem of the LIN limitation. Multi-frequency measurement also enables the correction for both parts of the complex signal in the case of an extreme conductivity where the LIN is not fully observed (Simon et al. 2014).

Coils geometries

As previously stated, the depth of investigation in the case of an EMI Slingram instrument is first of all defined by the inter-coils spacing and the geometry of the coil. We will consider here only the available geometries offered by the commercially available instruments which include HCP (horizontal coplanar), VCP (vertical coplanar) and PERP (perpendicular) configurations. These different geometries also provide different levels of complexity for the interpretation of the data. In the case of HCP, a deep magnetic source can create a negative anomaly where the same source in a shallow position will create a positive anomaly. In the case of 3D bodies, the interpretation of the anomalies is also complex because they may produce anomalies with shapes different from their sources. HCP has the deepest depth of investigation for the electrical conductivity measurement in 1D context but it also a shallower

depth of investigation for magnetic susceptibility. In the case of VCP, the depth of investigation is deeper for the magnetic susceptibility and shallower for the electrical conductivity. Depending on their design, EM instruments deliver different data values. The EM31, after correct calibration, delivers a measurement in mS/m , because it immediately undertakes the transformation given by McNeill's approximation. This approach is less accurate when using smaller coils spacing or when focused on magnetic susceptibility, in which case a full solution calculation may be required. In the case of the GEIV12, the instrument delivers a reading in ppm which requires one to undertake a conversion after acquisition with external software.

Soil physical properties

Magnetic susceptibility is generated by magnetic grains in the soil including magnetite, maghemite and hematite. These minerals are produced by fire, pedogenic process and are enhanced by human activities (Fassbinder et al. 1990). the introduction of organics and soil disturbance (Mannet 2000). The soil susceptibility range of values is quite large, from 1000 10^{-5} SI in volcanic areas to 10 10^{-5} SI, but values close to 1000 10^{-5} SI are rare.

Conductivity, the inverse of resistivity, is related to the clay content, degree of water saturation and the water salinity. In the frequency range where the displacement currents can be ignored (below 100 kHz). the electrical resistivity, ρ , is well defined and extends from 1 to 2×10^{11} in the intertidal zone to 10000 filia in permafrost or in crystalline dry soils (Telford et al. 1990). This very wide dynamic range is the greatest observed for usual geophysical properties, but values out of the 10^{-10} to 10^5 m may occasionally be observed in soil studies.

Instrumentation

Instruments

A range of commercial instruments are available to undertake electromagnetic induction investigations. Five companies share the largest part of the market: Geophex, Geonics, GE Instruments, GSSI and DualEM (Fig. 2). Geonics has historically been the most popular manufacturer. however, the use of GF Instrument and DualEM has grown considerably since they offer a multi-coils spacing and a steady calibration. Multi- frequency instruments (manufactured by Geophex and GSSI) became commercially available in the 1990s and their manufacturers argued that they allow simultaneous investigation of multiple depths, which can be selected by changing the investigation frequency. Unfortunately, this claim is not supported by experimental evidence. Nevertheless, these instruments do take measurements of the magnetic viscosity and allow for a robust correction to measure electrical conductivity and magnetic susceptibility.

The Geonics EM31 (Geonics Ltd) is the most commonly used commercial instrument, but it is mainly limited to conductivity measurements. The coils spacing is 3.66 m and the frequency is

9.8 kHz. Its use is limited only to measurements of electrical conductivity (with a maximum depth of investigation of 6 in). Unfortunately, the in-phase part of the signal is difficult to link to the magnetic susceptibility because of the large coils spacing. The Geonics EM38 (coils-spacing 0.5 meter and 1 meter) is well adapted to archaeological survey due to its small coils-spacing. The disadvantage of this configuration is that the in-phase zero of this instrument is extremely sensitive and can easily vary from day to day. This issue affects other instruments with small coils spacing. GF Instruments and DualEM now offer instruments with multiple coils spacing which means that they cover three simultaneous depths of investigation_

Other families of EMI devices that collect multiple frequency measurements include the Geophex GEM2 and the GSSI Profiler. These multi-frequency instruments offer a correction on the conductivity and the susceptibility measurement when the UN is not completely observed. We have successfully applied the GEM2 because it resists drift and the depth of investigation for the magnetic susceptibility is well adapted to archaeological targets. The Profiler should also be well-suited to archaeological purposes, particularly based on the slightly smaller coils spacing of this instrument (1.21 m compared to 1.66m for the GEM2).

The development of accurate GPS positioning allows one to survey large areas with EMI instruments. The NMEA code system is usually used to send the positioning to the instrument. The major part of the data logger used for the measurement manages this information and delivers data directly as an accurate map. Nevertheless when the interspace profile is small, some modifications must be applied. The velocity of the user generates a spatial offset between the measurement and the positioning. Also the time to process the positioning information and the EM measurement can create delay on the correlation of both data. Nevertheless, simple procedures can remove this effect by applying an offset, using the time or the direction of the acquisition (when the time is missing on the measurement).

Figure 2: Instruments in use in the field: CMD mini-explorer from GF instruments S.R.O. (Manataki, ISM Forth GEM2 from Geophex LTD). (Manataki, ISM Forth) and EM31 from Geonics LTD. (Hulin, Inrap).

Calibration

One of the most difficult steps for the collection of EMI data is the accurate calibration of the instrument. This measurement is undertaken with an electronic system, but temperature and the geometries of the instrument are a significant source of noise. Usually, instruments are designed to correct for temperature and geometrical drift. But these solutions are not completely efficient since drifting can be abrupt, especially for magnetic susceptibility measurements. For this reason it is essential to calibrate the instrument before each survey. There are a number of different solutions for EMI calibration (Sasaki et al. 2008), but the most effective is the solution applied by Thiesson et al. (2014). which works both for electrical conductivity and for magnetic susceptibility.

The steps for effective calibration are to find the coefficient and offset of the instrument. The coefficient is the ratio between the theoretical value and the experimental one, for both electrical conductivity and magnetic susceptibility for the same ground. Then we try to calculate the value of the offset, as the EMI instrument is not able to deliver a constant value of zero. Usually one can consider the coefficients for both parts of the complex signal. which is the procedure suggested for most commercial instruments. In reality this assumption is not valid and the coefficient could change considerably. Moreover, the calibration procedure is only available for the conductivity and not for the magnetic susceptibility measurement, which is unfortunate as this is more prone to electronic drift. For calibration of the conductivity, a vertical electrical sounding is applied using resistivity to create a model for the local soil. We do the simulation with the same characteristics for this model and then compare the theoretical and experimental value for two different heights of the EMI instrument from the ground. The comparison between the EMI and resistivity data gives us the value of the coefficient and the offset (between the theoretical value and the measured one) for the quadrature out-of-phase part of the signal. For the in- phase part of the signal we measure the response of the instrument for an aluminum ball of known volume and we calculate the ratio between the measurement and a model of the measurement. This ratio gives us the coefficient for the in-phase part of the signal. To determine the value of the offset for the quadrature-out-of-phase part of the signal we do a measurement at two different heights from the ground. As the sensitivity of the instrument is decreasing quickly with the height the value measured at two different altitudes (at least 2 m apart) is only affected by the conductivity. We then use the first modelling to remove this effect on the measurement.

Case studies

Three case studies (from the IGEAN project) (Sarris et al. 2014) are presented here to demonstrate how electromagnetic survey can successfully contribute to archaeological investigations. The first case study concerns the characterization of a paleo-channel which may have affected the spatial organization of a Neolithic tell site (magoula) in Thessaly. The second case study discusses the distribution of magnetic susceptibility at another Neolithic tell site,

showing differences on the treatment of soil. The last example shows how EMI methods can be useful to map buildings through the measurements of both magnetic susceptibility and electrical conductivity.

Palaeochannel mapping

Alinriotiki magoula is a Neolithic tell site located in the eastern coastal plain of Thessaly (Central Greece). A recent geophysical survey of the site revealed an extensive

settlement containing an abundance of near-surface architectural features. Most of the prehistoric settlement now lies within open agricultural fields where corn and wheat are cultivated. Geophysical prospection showed that a network of ditches or enclosures defined the spatial organization of the main settlement. The presence of fluvial channels passing next to the settlement was identified by aerial and satellite remote sensing.

For the EMI survey at Alinriotiki, a GEM2 from Geophex was employed, since it is well adapted for a deep characterization of electrical conductivity and a shallow characterization of the magnetic susceptibility. On the main settlement we used a line spacing of 1 m with differential GPS positioning and a line spacing of 5 m at certain peripheral parts of the settlement. The spacing between the measurements was chosen on the basis of the depth of investigation and the size of the targets. In this particular case the target is large (the palaeochannel) and the depth of investigation close to 2.5 meters. The primary use of the EMI instruments in this survey was to measure the conductivity to map changes in soil composition. Palaeochannel sediments often have a different conductivity from sediments from rivers and floodplain deposits due to changes in lithology, porosity and water saturation. The profile of the fluvial system during deposition controls the nature of the sediments contained in it: steep (usually braided) systems are characterized by gravels and sands with high porosity values and flatter (usually meandering or anastomosing) systems are characterized by finer grained sediments and lower porosities.

The south part of the site shows a low value of conductivity which indicates the presence of low clay content in the soil. At the northwest, the conductive sediment is crossed by a relatively resistive anomaly. If we consider the likelihood that this part of the settlement was influenced by palaeochannel activities, these resistive remains could match with a gravel or sand ridge from sediments caused by faster fluvial activities. The low conductivity in the north and northeast part of the site might also explain the absence of magnetic anomalies in this localized area which were damaged by the palaeochannel or were prevented from expanding further to the north.

Sail use: The magnetic susceptibility as a relevant proxy

Magnetic susceptibility can be an excellent proxy for the anthropogenic use of space, especially due to workshop activities and the introduction of organic material into the soil. The Neolithic tell of Belitsi in eastern Thessaly was investigated using a magnetometer; however, an overabundance of pottery sherds on the surface and the disturbed surface overwhelmed the signal and made it difficult to define the geometry of the settlement (Vouzaxakis 2008). Despite this difficulty, magnetic survey was able to locate a circular ditch delimiting the boundaries the site, but on top of the tell only a fuzzy disturbed area was indicated without any clear evidence of buildings. Magnetic susceptibility (GEM2, HCP measurements) was used with a 1 m line spacing, but it too was unable to extract a more accurate picture of the site (Fig. 4).

Figure 3: Map of the apparent electrical conductivity (GEM2, HCP) at Almiriotiki. Overlap of the map with a DTM created by photogrammetry. The map shows the high conductivity (in blue) associated with the palaeochannel on the east and north parts of the site.

Only some anomalies can be related to buildings on the top of the magoula and it is difficult to distinguish between archaeological features and noise originating from surface scrap metal, sherds and the olive trees which cover half of the site today. Aside from this observation, there is an overall increase of the magnetic susceptibility all around the site and delimited by a ditch visible on the magnetic survey. The overall increase of magnetic susceptibility is an indication of the anthropogenic activities on the site as an enrichment of organic matter. Determining the exact cause of the enhancement of the magnetic susceptibility requires laboratory analysis of the soil to study the mineralogy and grain size of the magnetic minerals causing. The lack of specific anomalies in this area can be explained either by the high background magnetic susceptibility values overwhelming the rest of the features, or by a heavy disturbance of the soils due to cultivation.

Neolithic enclosures

The Neolithic site of Perdika 2 in the eastern Thessalian plain was mapped by four different geophysical methodologies (magnetics, electrical resistivity, EMI, GPR). The site is located on the level plateau of a natural hill. EM measurements were done with the GEM2 with a 1 m line spacing all around the site. The results from this survey showed a strong correlation to those from the magnetometer (Fig. 5). Both techniques suggested a complex enclosure system, which is not visible on the surface. The curvilinear anomalies which define these enclosures are clearly magnetic and probably relate to a system of enclosures and internal divisions.

There is a complicated correlation between the conductivity results and the magnetic susceptibility results from these features, with some areas being defined by high conductivity and some by low conductivity. This suggests that the enclosure was made up of walls (conductivity low) and the internal fluctuations of the conductivity may indicate various activities within the settlement (Fig. 6). This hypothesis awaits further investigation, but highlights the utility of measuring two physical properties for the interpretation of archaeological features.

Figure 4: Neolithic site of Belitsi in Thessaly: A. Map of magnetic anomalies and B. Overlap of the magnetic susceptibility (GEM2, HCP) on the magnetic anomalies.

Figure 5: Neolithic site of Perdika 2. Left: Map of the magnetic susceptibility (GEM2, Frequency = 5020Hz, HCP). Right: Vertical magnetic gradient data resulted from the SENSYS magnetometer survey.

Figure 6: Electrical conductivity (color-scale) and magnetic susceptibility (black and white) at the Neolithic site of Perdika 2. Several local conductive anomalies are observed in various sections of the settlement, probably related to different activities within the site.

Conclusion

EM methods have proved to be an essential tool for the characterization of archaeological sites and palaeo- landscapes. The great variety of instruments offers measurement ranges and device configurations suitable for any application. The possibility to add a global positioning system during the acquisition enlarges the coverage area from less than one hectare to more than two hectares per day. The new method proposed here regarding the use of this multi-frequency instrument corrects the measurement when the UN limitation is not fully respected and obtains a measurement of the magnetic viscosity and dielectric permittivity. For both properties, some further work needs to be done in order to better understand the relation between the archaeological remains and the physical properties and to find the best way to carry out this kind of measurements. These new developments mean that EM methods are becoming even more useful and will become an even more important tool for archaeological prospection.

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