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François-Xavier Simon, Julien Thiesson, Alain Tabbagh

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Which EM Properties with Multi-frequency Low Induction Number Slingram Apparatus?

F.X. Simon (INRAP), J. Thiesson (UPMC), A. Tabbagh* (UPMC)

Summary

In the 3 kHz – 300 kHz frequency range, electromagnetic measurements achieved with limited size Slingram instruments are not only sensitive to the electrical resistivity but also to the complex magnetic susceptibility and to the electrical polarization. A process allowing the determination of all the properties is proposed and applied to case studies with the use of commercial instruments.

Introduction

Metric dipole-dipole, or Slingram, electromagnetic induction (EMI) instruments are commonly used to map the characteristics of the first metres (sub-surface) of the ground, in a wide range of applications including archaeological prospection and soil studies (proximal sensing). As a consequence of the principle of EM induction, these devices have been, and still are, considered as conductivity (σ) meters. However, in the context of archaeological prospection, experience in the field has shown that these instruments can also be used to assess the presence of a magnetic susceptibility (κ) response. As a consequence of the “low induction number” condition, the conductivity response is in quadrature with the primary field, and can thus be separated from the in-phase magnetic susceptibility response, allowing for the simultaneous measurement of these two properties (Scollar *et al.* 1990). However, the soil’s magnetic susceptibility is a complex quantity, the quadrature component of which thus adds (or subtracts) to the conductivity response, making it difficult to interpret over low conductivity terrains. It was recently pointed out by Benech *et al.* 2016 that electrical polarisation can also contribute to the complexity of these measurements. Thus, for an accurate interpretation of EMI measurements, and in order to compare EMI maps with ERT or laboratory results, one must take four real quantities into account. These can be grouped together in the form of two complex quantities: $\kappa = \kappa_{ph} - i\kappa_{qu}$ (1) for the sub-surface magnetic properties, and $\sigma^* = \sigma + i\omega\epsilon_0\epsilon_r$ (2) for its electrical properties (ω being the angular frequency, ϵ_0 the permittivity in vacuum, and ϵ_r the relative permittivity).

When only one frequency is used, there are just two independent measured quantities: the in-phase and quadrature responses, such that it is not possible to find a solution for the four unknown properties. This limitation can be overcome through the use of a multi-frequency apparatus.

For the frequency range of interest (3 – 300 kHz) σ is constant, ϵ_r is not well known and is highly variable, κ_{ph} is nearly constant (it decreases slowly with increasing frequency) and κ_{qu} is constant. The magnetic properties verify the relationship:

$$\frac{2}{\pi} \kappa_{qu} = - \frac{\partial \kappa_{ph}}{\partial \ln \omega} \quad (3) \text{ (Dabas and Skinner 1993).}$$

Although the depth of investigation varies with frequency, both the theory and experimental evidence show that at low induction numbers this variation is negligible, except for the case of highly conductive media (tidal zones).

In the following we provide a brief theoretical illustration of the role of each of the aforementioned properties, and present two case studies in which two different commercial, multi-frequency devices were used: the EMP400 (GSSI) and the GEM-2 (Geophex).

Theoretical role of each property

We consider a reference case, where the instrument is used in the HCP configuration, has a 1.5 m separation between the transmitting and receiving coils, and is operated at a 0.25 m clearance above the ground. Two different frequencies are considered: 4 kHz and 100 kHz. The ground below the surface is assumed to be homogeneous, with $\sigma=0.01 \text{ Sm}^{-1}$, $\epsilon_r=200$, $\kappa_{ph}=100 \times 10^{-5} \text{ SI}$ and $\kappa_{qu}=0.06\kappa_{ph}$. Fig. 1 shows the in-phase (red) and quadrature (blue) components of the secondary field, normalized by the modulus of the reference case response. Each property is varied from 0.1 to 10 times the value used in the reference case (with the quadrature magnetic susceptibility always adjusted to 6% of the in-phase susceptibility).

It can be seen that at 4 kHz, variations in relative permittivity have no effect on the secondary field, whereas the quadrature response remains proportional to the conductivity, and the in-phase response remains proportional to the in-phase susceptibility. As a consequence of the HCP configuration, the quadrature magnetic susceptibility response is opposite to that of the conductivity. At 100 kHz the

ground responses generated by both σ and ϵ_r increase monotonously as a function of the frequency. Although weaker than that of the conductivity, the influence of relative permittivity is significant, and slightly higher than that of the magnetic susceptibility.

In order to determine the four desired quantities through the use of a multi-frequency instrument, several steps are implemented: (1) two frequencies are selected from the lower portion of the frequency range, allowing the parameters σ , κ_{ph} and κ_{qu} to be determined; (2) the magnetic susceptibility responses are computed at one or more frequencies in the upper portion of the frequency range; (3) σ and ϵ_r are determined at each of the selected “high” frequencies.

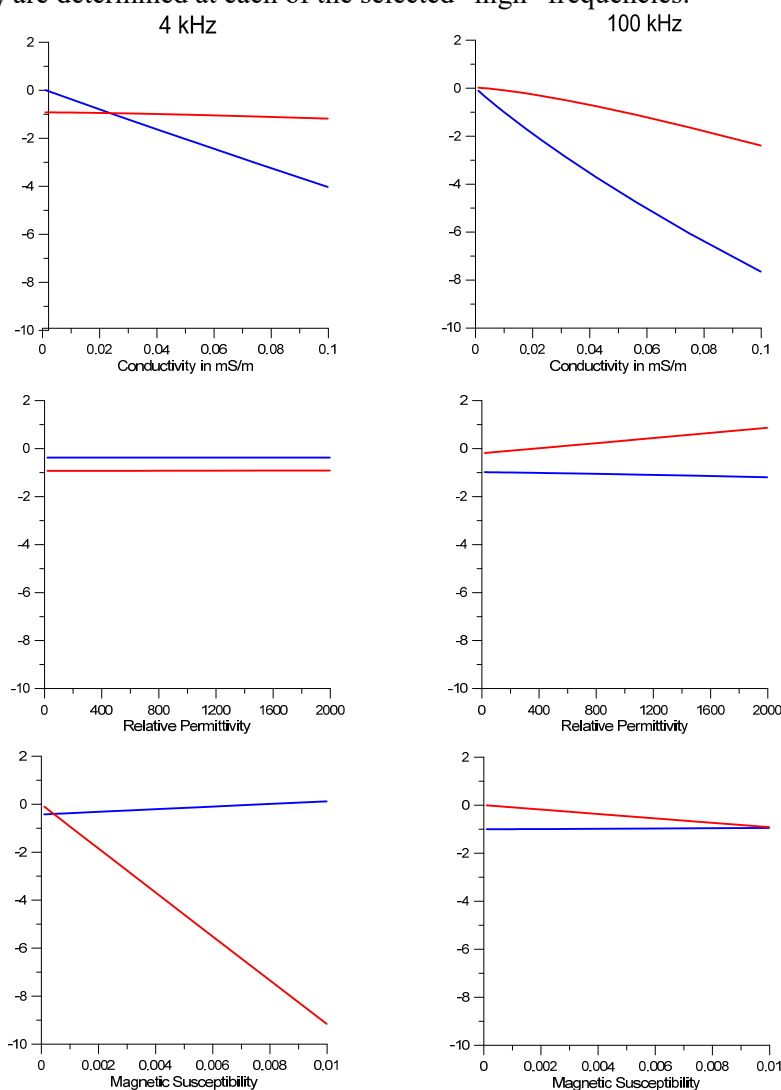


Figure 1 In-phase (red) and quadrature (blue) components of the secondary field as a function of the conductivity, relative permittivity and magnetic susceptibility. These components are normalized by the modulus of the secondary field determined for the reference case at 4 kHz, and at 100 kHz.

First example: Narse de la Sauvetat (Puy de Dôme, France)

The EMP400 was used in the VCP configuration with a clearance of 0.25 m above the ground, at three different frequencies: 5 kHz, 8 kHz and 15 kHz. The study site, which is located in the volcanic region of the French *Massif Central*, comprises several small Gallo-roman buildings made of resistive and magnetic basalt, overlaying a circular enclosure. The relative permittivity cannot be measured in these locations, as the frequencies used by the EMI instruments are too low.

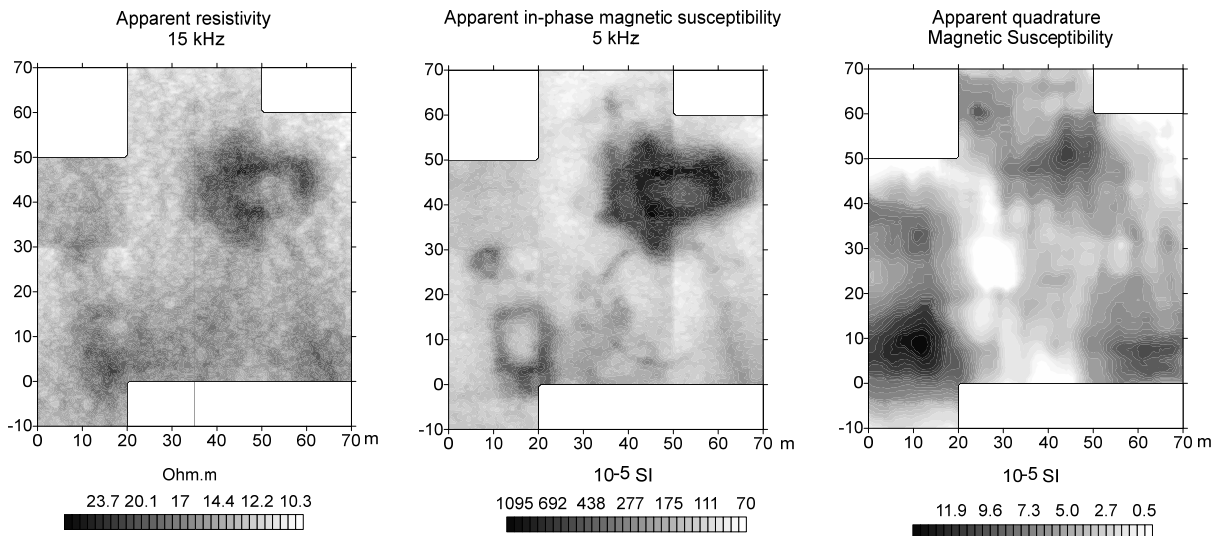


Figure 2 Narse de la Sauvetat: apparent resistivity, in-phase and quadrature components of the apparent magnetic susceptibility.

A past context of sedimentation is thought to have led to the accumulation of thin particles, and thus to the ground's low resistivity. As a consequence of the site's volcanic environment, the in-phase magnetic susceptibility is high, whereas the quadrature susceptibility remains low, thus suggesting a high proportion of single-domain magnetic grains. The archaeological features are more clearly delineated by the susceptibility map, because the volume of soil they account for is lower than in the case of the conductivity measurements.

Second example: Neolithic site of Perdika 2 (Greece)

The GEM-2 measures the difference between two receiving coils located at 1.66 m and 1.035 m from the transmitter. This device was used in the HCP configuration, with a 0.3 m clearance above the ground, and at five different frequencies: 4.95 kHz, 10.23 kHz, 21.03 kHz, 43.35 kHz and 89.43 kHz. The study site is located on the eastern Thessalian plain, and corresponds to a Middle Neolithic settlement, which can be recognized mainly by its complex ditch system, and was probably associated with a multi-phase occupation.

Two of the resistivity maps (Fig. 3) reveal a small decrease in resistivity at higher frequencies, although the images are very similar. Unfortunately, there is no obvious correlation between these maps and the archaeological features, ditches and entrances, clearly revealed by the in-phase magnetic susceptibility map. Although the maps of magnetic viscosity and in-phase susceptibility are different, the ratio κ_{qu}/κ_{ph} is higher at this site than in the volcanic context of Narse de la Sauvetat. Similarly to the variations in resistivity, those corresponding to the permittivity are not clearly correlated with the archaeological features identified by the susceptibility map. The permittivity decreases with frequency: at 43.35 kHz the median value is 1250 and the interquartile value is 245, whereas at 89.43 kHz these values decrease to 914 and 128, respectively.

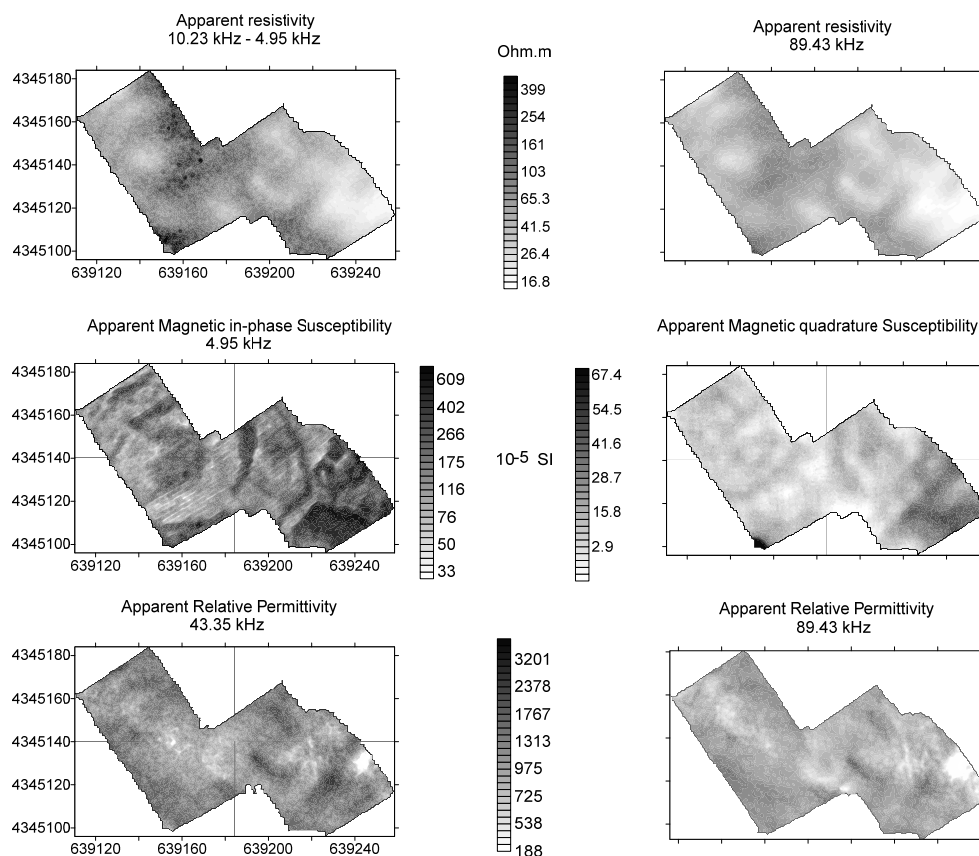


Figure 2 Neolithic site of Perdika2 (Greece). Apparent resistivity computed from the difference between the quadrature responses at 10.23 kHz and 4.95 kHz, and at 89.43 kHz. In-phase and quadrature apparent magnetic susceptibilities. Permittivity at the two higher frequencies.

Conclusions

Multi-frequency EMI instruments make it possible to distinguish between different electromagnetic properties of the ground, and the mapping of their own variations. Furthermore, the two examples provided here show that additional information can be retrieved when all of the electromagnetic properties affecting EMI measurements are analysed. Resistivity and permittivity data can provide a greater volume of investigation, with significantly useful information concerning the pedological/geological context of the site. It is more convenient to use the magnetic susceptibility to delineate the smaller archaeological features.

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