Complex Susceptibility Measurement Using Multi-frequency Slingram EMI Instrument

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SUMMARY

Complex magnetic susceptibility is a well-known property both theoretically and experimentally. To achieve this measurement, different ways have been tested, like TDEM or multi-frequential measurement on soil sample. In this study we carry out the measurements by the use of a multi-frequential EMI Slingram instrument to collect data quickly and in-situ. The use of multi-frequency data is also a way to correct effects of the conductivity on the in-phase component and effects of the magnetic susceptibility on the quadrature component of the raw signal.

Introduction

The use of EMI devices for soil mapping is well-known, especially for the measurement of electrical conductivity in environmental or archaeological studies. To neglect displacement currents, the used frequencies are lower than 100 kHz. According to the low induction number (LIN) approximation, conductivity is in quadrature out of phase from the transmitter moment which allows the measurement of the magnetic susceptibility on the in-phase part of the signal. Under this approximation also the depth of investigation only depends on instrument geometry, meaning the choice of coils spacing and orientations.
Although EM instruments are built to avoid any conductivity dependence in the in-phase part signal, in practice the measurement could be more complex. In the case of a high conductivity, a part of the in-phase measurement is generated by the conductivity (and the LIN approximation is not fulfilled) and in the case of a low conductivity the part of the out-of-phase measurement related to the magnetic susceptibility can be significant. The use of different frequencies has been proposed to correct both effects (Tabbagh 1986) and moreover it allowed the measurement of the quadrature part of the magnetic susceptibility (Benech 2000).

Studies on soil samples and TDEM measurements in the field have shown that the magnetic susceptibility is a complex quantity (Mullins and Tite 1973, Dabas and Skinner 1993). According to the dispersed single-domain grain theory, the imaginary part κ_{qu} called the magnetic viscosity and the real part κ_{ph} of the magnetic susceptibility are linked by the following relation:

$$\frac{2}{\pi}\kappa_{qu} = \frac{\partial \kappa_{ph}(\omega)}{\partial Ln(\omega)}$$

It means that the in-phase magnetic susceptibility is a frequency dependent quantity and the out-of-phase magnetic susceptibility a non-dependant one. In common soils the quadrature part of the magnetic susceptibility is approximately 6% of the in-phase part. The knowledge of the magnetic susceptibility components is particularly interesting for determination of the size of the magnetic grains and is related to the nitrogen and carbon contents (Thiesson et al. 2012).

In the case of EMI Slingram measurement, the response generated by the imaginary part of the complex susceptibility adds algebraically to the one generated by the conductivity in the quadrature out-of-phase component of the signal. Nevertheless, the response of the quadrature part of the signal due to the conductivity increases with frequency, unlike the magnetic susceptibility. The use of different frequencies therefore allows separating the conductivity and the magnetic viscosity responses.

Instrument and method

To manage these multi-frequency measurements we used the GEM2 (Geophex, ltd). It is a broad-band instrument with a coil spacing of 1.66 m (Won *et al.* 1996). The two coils are Co-Planar allowing measurement in both HCP and VCP modes. One can choose 5 different frequencies between 300 Hz and 90 kHz, with an algebraic or a logarithmic progression. The instrument is not a simple dipole-dipole one because it includes a bucking receiver coil at 1.035 m from the transmitter coil and the measured quantity is the difference between responses at the two receiver coils. Any interpretation must also use this difference and not the signal at the 1.66m coil.

One first achieves a calibration of the instrument by comparing the result of a vertical electrical sounding and GEM2 measurements at two different heights. This allows relating the measurements' digits to true ppm ratios and to estimate the offsets of the instrument in quadrature. Then, at each measurement point, the apparent conductivity is determined from the difference between the quadrature responses at two different frequencies, which remove the quadrature responses of the magnetic susceptibility. This difference in ppm is converted in electrical conductivity by referring to the theoretical curve relating the conductivity (in mS/m) and the difference in the responses in ppm. Having the apparent conductivity value, it is then possible to calculate both in-phase and quadrature responses generated for each frequency and to remove them from the experimental responses. The responses generated by the in-phase and out-of-phase components of the magnetic susceptibility were obtained for 5 frequencies. By referring to theoretical responses those are expressed in terms of the apparent complex magnetic susceptibility.

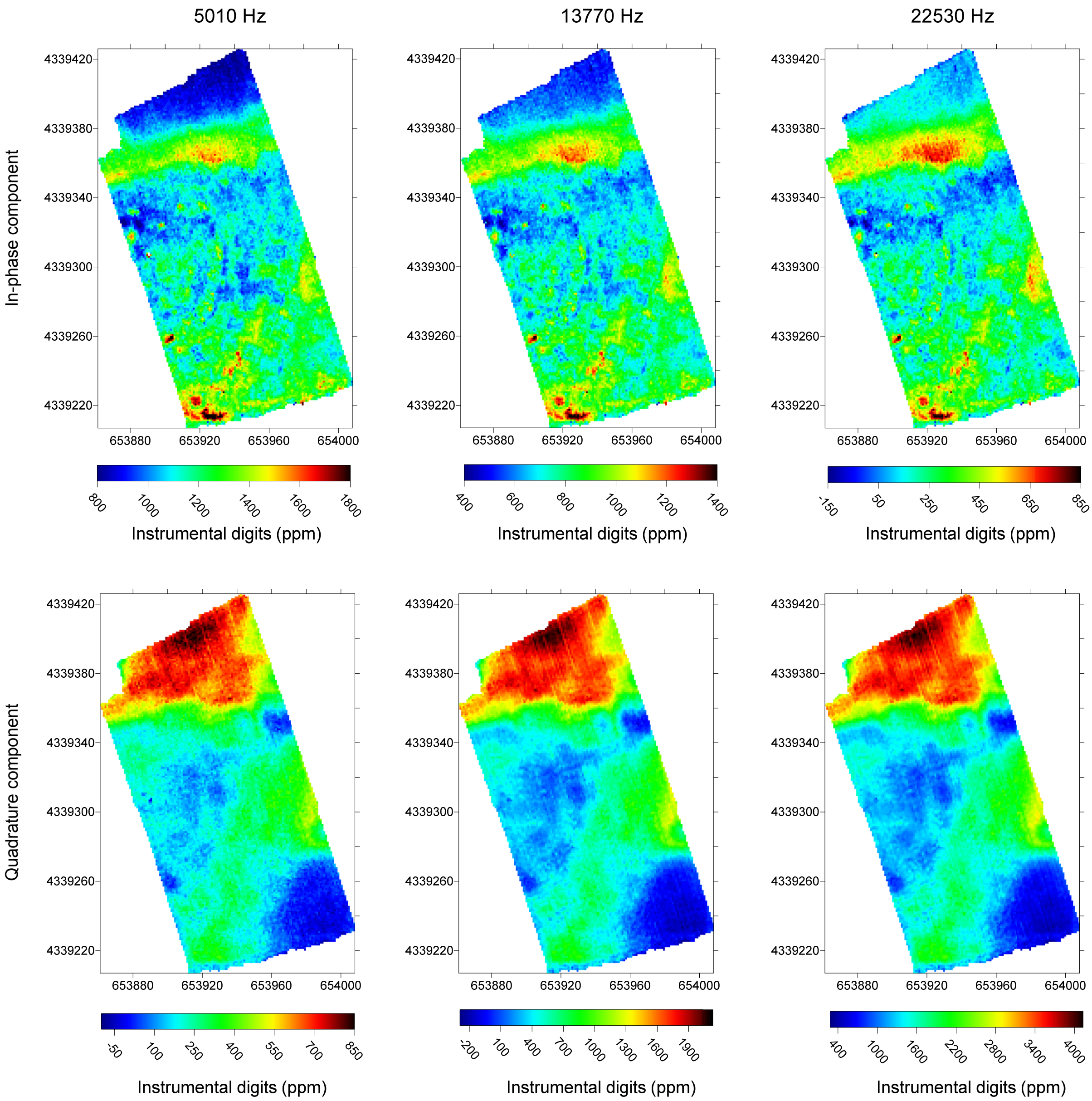

Figure 1 *<u>Map of GEM-2 raw data</u> for 5010 Hz, 13770 Hz and 31290 Hz for in-phase (top) and quadrature out-of-phase component of the signal (bottom). For the quadrature the three different frequencies show a non-dependency on the frequency but for the in-phase signal we observe different offsets between the frequencies.*

Example

The particular methodology was used on the archaeological site of Almiriotiki magoula, in Almyros, Thessaly (Greece) to map the spatial organization of the Neolithic settlement. Data were collected with a handle system and GPS-RTK positioning. The survey was carried out along parallel profiles one meter apart with a frequency of acquisition of 1 Hz. We used 5 different measurement frequencies: 5010 Hz, 133700 Hz, 22530 Hz, 31290 Hz and 40050 Hz. The instrument was carried at an altitude of 0.3 m from the ground.

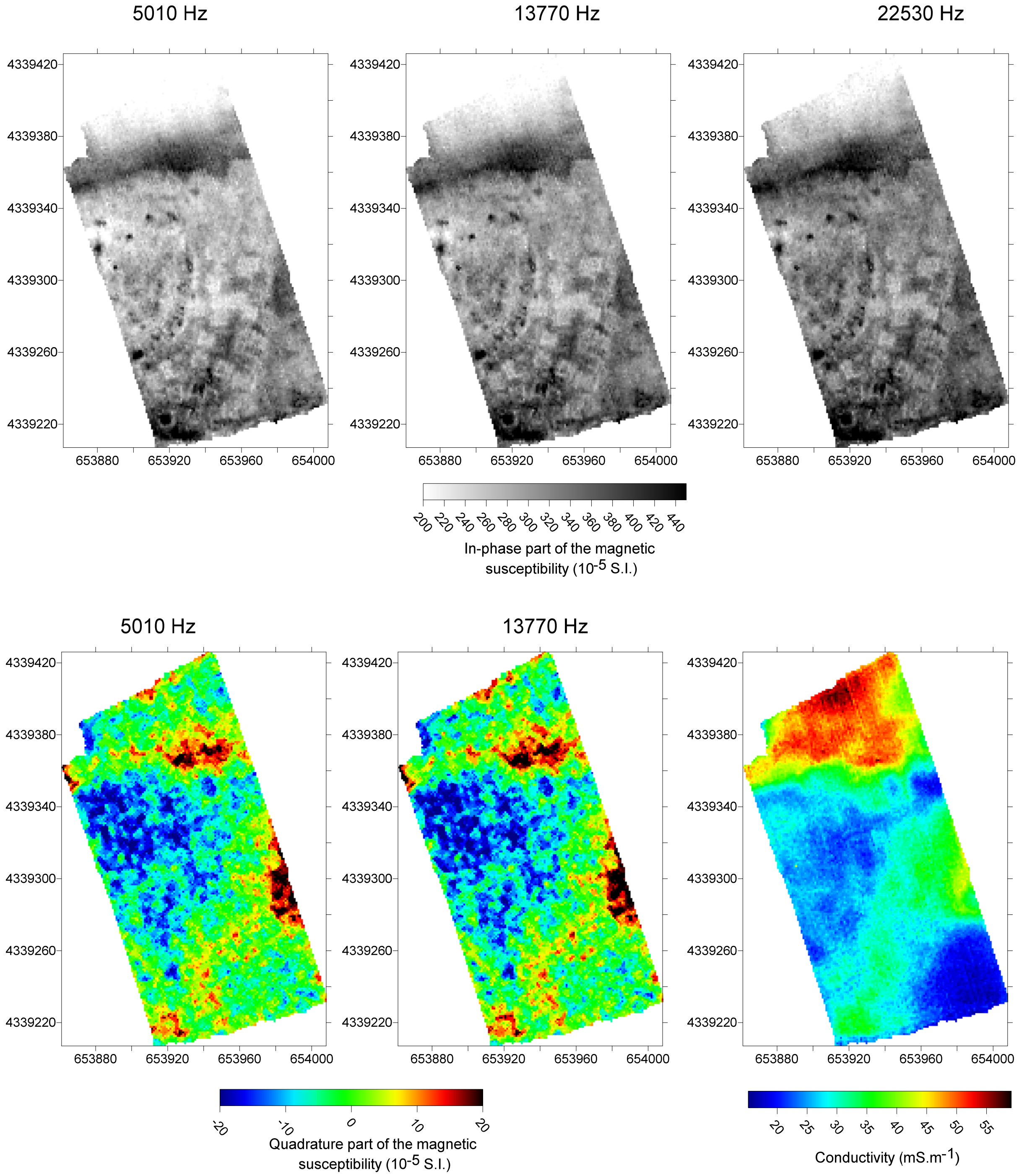

Figure 2 *Map of the GEM-2 processed data: On the top, maps of the in-phase components of the magnetic susceptibility, for 5010 Hz, 13370 Hz and 31290 Hz. On the bottom, maps of the quadrature components of the magnetic susceptibility for 5010 and 13770 Hz and of the conductivity (to the right). We observe an increase of the in phase susceptibility offset at the different frequencies. The quadrature components of the magnetic susceptibility, in accordance with the theory, are non-dependent of the frequency.*

On the raw data (Figure 1) we don't see any differences on the quadrature component of the signal for the different frequencies except the multiplicative effect of the frequency itself. For the in-phase component of the raw signal, some differences, especially to the north part of the map are related with the conductivity effects. Offsets for each frequency and each component suggest the requirement of a calibration.

After processing (Figure 2), we obtain the conductivity, the in-phase magnetic susceptibility and the quadrature component of the magnetic susceptibility. The conductivity is high which explains its contribution in the in-phase components of the raw signal for the highest frequencies. For the in-phase magnetic susceptibility the three different frequencies show different zero adjustments partially induce by a poor calibration and by the complex variation of sign of the anomaly with depth in HCP (especially with contribution of the bucking coils). This particularity involves also a complex interpretation of the apparent susceptibility in HCP configuration; the shallow part of the soil may create a negative value of apparent magnetic susceptibility while the deeper strata can produce a positive one. Nevertheless, with some a priori on the context, it could be also informative about the depth of detected features. One observes that the relationship between quadrature and in-phase values is not far from the 6% value and that quadrature values don't change with the frequency according with the theory.

Conclusion

The used multi-frequency EM instrument allowed the measurement of the quadrature part of the magnetic susceptibility by the processing of data collected at different frequencies. Due to the information born by the complex magnetic susceptibility such measurements open new paths in soil properties' mapping that will be very interesting to study. The use of multi-frequency can also be improved, for instance by using frequencies close to 100 kHz, to determine the dielectric permittivity in this part of the low frequency range (Huang and Fraser 2002). Still, effects of polarization are probably not negligible and this property needs to be taken into account for a precise determination of the conductivity.

Acknowledgement

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