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Contribution of the Magnetic Horizontal Gradient Operator (MHGO) for the Interpretation of the Magnetic Anomalies

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SUMMARY

In this paper, we propose a high-resolution approach for detecting magnetic source boundaries. It depends on the application of the magnetic horizontal gradient operator (MHGO). The MHGO emphasizes the source effects, reducing the interference effects of the anomalies and yield an enhanced image of the boundaries.
In order to illustrate the efficiency of the method, we describe the results obtained on the two archaeological sites: “Villa degli Antonini” (Genzano, Rome) and Rota Ria (Mugnano in Teverina, Viterbo) by the application of the detailed magnetic surveying. The results obtained have shown that the source boundaries locations are more precisely determined compared to those obtained with other known techniques which use the vertical gradient of the magnetic field.
Since the main goal of the investigation was to understand and to high light the nature of the magnetic anomalies, different geophysical techniques (Electromagnetic and Ground penetrating radar surveying) were carried out. The final step of the investigation was the excavation in the targeted sector of the study areas in order to test the validity of the geophysical interpretations.
The most interesting result was that, in both cases, the excavations have confirmed the results obtained during the magnetic surveying.

Introduction

Magnetic methods have become important tools for the scientific investigation of archeological sites, with magnetic prospecting survey being the most prominent ones. One of the most important steps in the interpretation of the potential field data is to provide information on the horizontal location of the causative sources and their depth.
In this work, it is intended to highlight the important role of the magnetic horizontal gradient operator (MHGO) in detecting the magnetic source boundaries. MHGO was generated from a grid of vertical gradient of the magnetic field. The MHGO is reported as a number, which represent the amount of the magnetic anomalies in each square meters. The method can be applied directly to obtain the maxima values of horizontal gradient anomalies indicating the source boundaries. Consequently, this will reduce the interference effects and at the same time will provide an enhance image and yield a more precise delineation of magnetic bodies. In order to illustrate the efficiency of the method, we describe the results obtained on the two archaeological sites: "Villa degli Antonini" (Genzano, Rome) (hereafter VA) and Rota Ria (Mugnano in Teverina, Viterbo) (hereafter RR) by the application of the detailed magnetic surveying.
Since the main goal of the investigation was to understand and to high light the nature of the magnetic anomalies, different geophysical techniques (Electromagnetic and Ground penetrating radar survey) were carried out. The final step of the investigation was the excavation in the targeted sector of the study areas in order to test the validity of the geophysical interpretations.

Archeological sites

Villa degli Antonini (VA) – archeological framework.

Among the major elite residences in the area of the Alban Hills, the "Villa degli Antonini", located at the eighteenth mile of the Via Appia, in the ancient Ager Lanuvinus, is so far the least explored (Fig. 1a). In 1996 a brief clearing of the area immediately west of the baths brought to light part of a large curvilinear structure that was not further explored at the time (Fig. 1a). Our major goal was to understand the nature and the chronological development of this curvilinear structure.

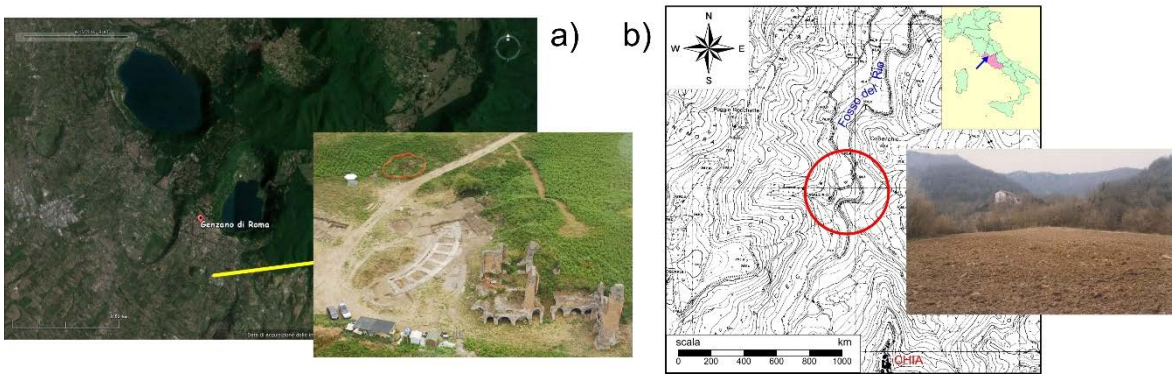

Figure 1 *Location of the archeological sites: a) Villa degli Antonini (VA) and b) Rota Ria (RR).*

Rota Ria (RR) – archeological framework

The Rota Ria, the second test-area of this study, is located in the heart of the Central Apennines, in the northern Latium region. It falls inside of the Viterbo province and specifically on the territory of the Mugnano in Teverina village, next to Rio creek (Fig. 1b). At the time, we found a large green meadow. The overall extended of the settlement was completely unknown. The idea was to check the settlement structure against ground topography before excavation.

Magnetic data acquisition and processing

The Montclair State University, for the test-area of VA and the University of Tuscia, for the test-area of RR in collaboration with the department of Earth Sciences of the University of Rome "La Sapienza" undertook an ongoing systematic study of the sites through different means of investigation, including archaeometric analysis and geophysical survey, in order to indicate the distribution of the buried archaeological features (Chatr Aryamontri, 2015).
Within this framework, both the geological environment and the buried remains suggested the use of magnetometry investigation.
The magnetic data were collected using a Geometrics G856 in gradiometer configuration (two sensors mounted on a vertical staff at a distance of 1m apart). 1170 stations spaced at 1m intervals, with a sampling step of 1m and 250 stations spaced at 2m intervals, with a sampling step of 2m, were executed to cover an area of 2170 square meters in the VA test-area. Instead, the study area of the RR was divided into two sectors of variable size (west sector of 5200 square meters and east sector of 5000 square meters), that were surveyed separately. 1340 stations for the west sector and 1260 stations for the east sector, spaced at 1m intervals, with a sampling step of 1m, were executed in order to provide the maps of the vertical gradient of the magnetic field (Fig. 2a and 3a).
In order to obtain the lateral boundaries of the main causative sources of magnetic anomalies, a technique without the reduction-to-the-pole (RTP) was adopted. The map of magnetic anomalies (Fig. 2b and 3b) was computed by the magnetic horizontal gradient operator (MHGO). The differential and integral calculus of the magnetic gradient operator (MGO) generates a grid of steepest slopes (i.e. the magnitude of the gradient) at any point on the surface. The MGO is reported as a number, which represent the amount of the magnetic anomalies in each square meters.
The definition of the gradient yields the following equation:

$$HG\ (x,y) = \left[\left(\frac{\delta H}{\delta x}\right)^2 + \left(\frac{\delta H}{\delta y}\right)^2\right]^{\frac{1}{2}}$$

where $(\delta H/\delta x)$ and $(\delta H/\delta y)$ are the horizontal derivatives of the magnetic field in the x and y directions, respectively (Setyawan *et al*., 2015).

The maps reveal the better resolution of the MHGO with respect to vertical gradient. In fact, in the case of the VA test-area (Fig. 2) the maxima of the vertical gradient are not able to delineate the boundaries of the magnetic source and the information they bring is limited to a rough outline of the positions of the anomalies. More interesting results are instead obtained from the MHGO, whose maxima encircle a number of anomaly source bodies, delineating their boundaries. Even in the case of the RR test-area, the boundaries of the magnetic source inferred from the proposed technique are more impressive than those obtained with the vertical gradient of the magnetic field (Fig. 3).

Geophysical Surveys and excavation strategy

In order to determine the exact shape and therefore the best excavation strategy for these buried archeological structures, a series of different geophysical investigations were carried out, allowing for the most effective possible verification of the quality and reliability of the acquired data and its elaboration (Di Filippo *et al*., 2006). To this aim, the electromagnetic induction techniques (EMI) and ground penetration radar were combined with the magnetic surveying for the VA test-area. This multi-methodological approach allowed a more accurate detection and mapping of the underground walls and floors.
The EMI survey was carried out by means of the GSSI Profiler EMP-400 electromagnetic induction tool. The conductivity map (Fig. 4), shows the presence of several significant anomalies, having a clear correspondence with the horizontal gradient of the magnetic field.
Finally, a Ground penetration radar (GPR) survey was carried out to refine the EMI interpretation and identify the sources of EM anomalies. The GPR data were obtained by means of a GSSI Sir10B GPR

system using an antenna with a center frequency of 400 Hz. Fig. 4 is a GPR interpretative map showing the locations of targets highlighted.

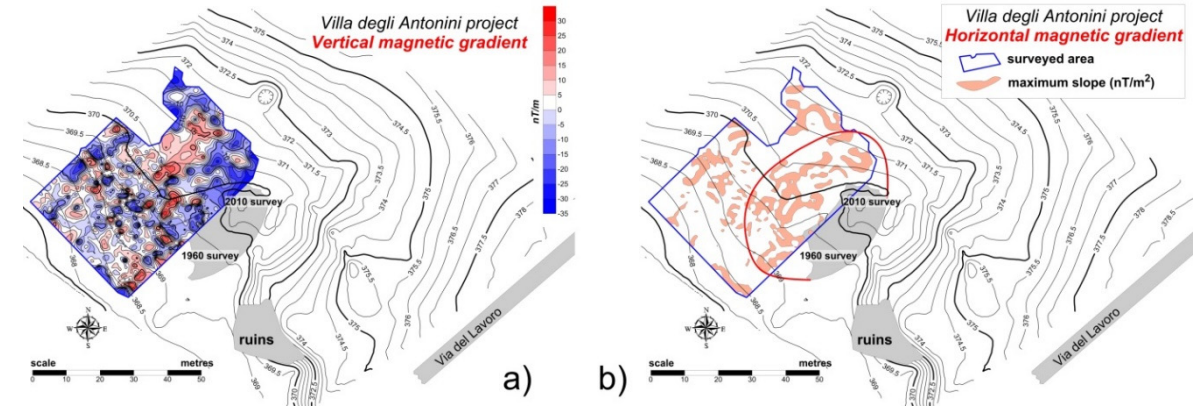

Figure 2 *a) The vertical magnetic gradient map and b) the horizontal magnetic gradient map of the magnetic data for the VA test-area.*

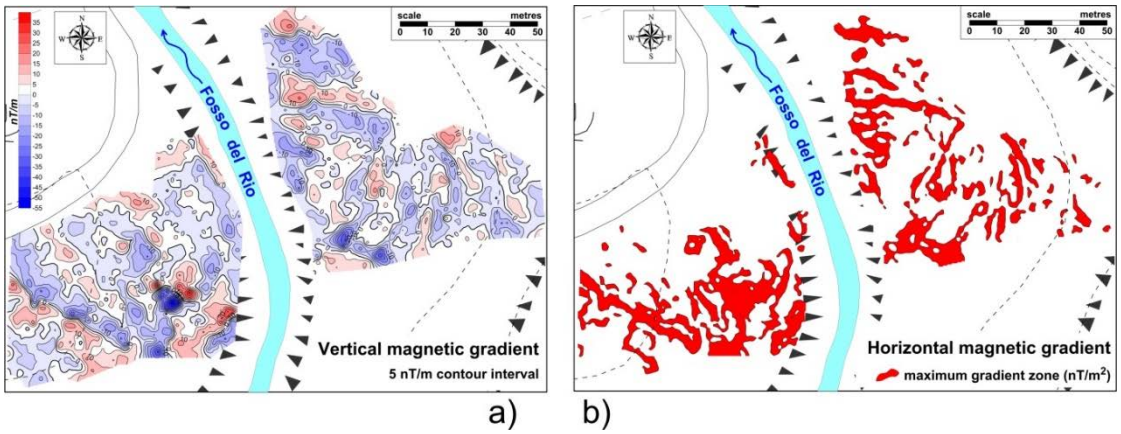

Figure 3 *a) The vertical magnetic gradient map and b) the horizontal magnetic gradient map of the magnetic data for the RR test-area.*

In order to test the validity of the geophysical surveys and understand the nature of the so called "curvilinear structure", we have so far excavate only in a targeted sector of the area of the anomaly called "Saggio A". "Saggio A" has confirmed that the curvilinear structure is indeed an amphitheater (ca. 50x25 m), where the emperor Commodus, according to the ancient sources, performed the animal hunt spectacles for which he earned the nickname "Roman Hercules" (Di Nezza *et al*., 2015).
On the RR test-area the excavation has confirmed the results obtained during the magnetic surveying, bringing to light the presence of two furnace and the structures of buried walls made of peperino and tuff blocks. A wall made of tuff blocks can be observed even from the western sector of the Rio creek.

Conclusions

We presented an interpretation of the magnetic anomalies at two test-areas (VA and RR), caused by the distribution of the buried archaeological structures. The application of the magnetic horizontal gradient operator (MHGO), will reduce the interference effects and at the same time will provide an enhance image and yield a more precise delineation of magnetic bodies. The results obtained have shown that the source boundaries locations are more precisely determined compared to those obtained with other known techniques which use the vertical gradient of the magnetic field. In order to determine the exact shape and therefore the best excavation strategy for these buried archaeological structures, a series of different geophysical investigations (Electromagnetic and Ground penetrating radar surveying), were carried out.

The most interesting result was that, in both cases, the excavations have confirmed the results obtained during the magnetic surveying.
The authors think that this method, which has been successfully applied on these two test-areas, can be used as an efficient tool for the accurate interpretation of magnetic anomalies.

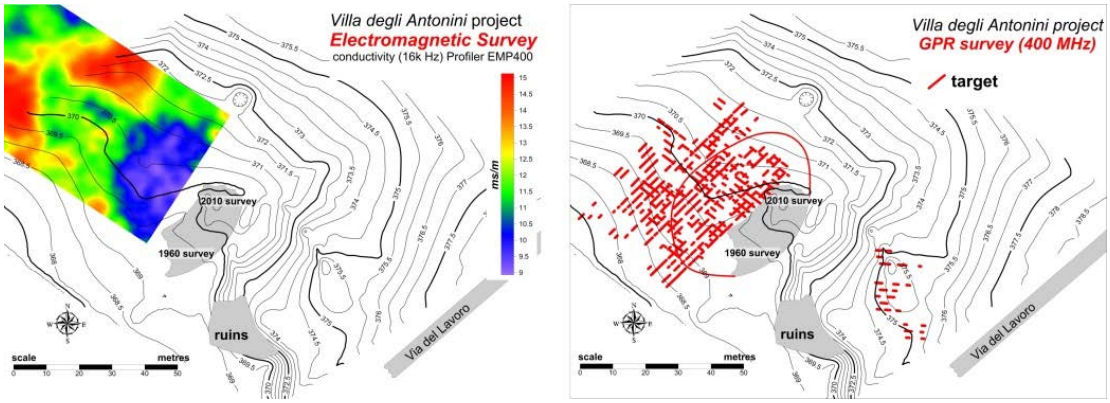

Figure 4 *Electromagnetic and Ground penetrating radar surveys at the VA test-area.*

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