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Examples of ac resistivity prospecting in archaeological research

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Abstract
In this paper we present the results of an alternating current resistivity survey, with a view to future tomographic processing. Two examples are given to evaluate the validity and the resolution of the method. The first in the Sabine Necropolis of Colle del Forno (Montelibretti, Rome), the second in the Etruscan settlement of Poggio Colla (Vicchio, Florence). All the measurements were carried out utilising current up to 512 Hz and a mobile dipole MN along straight lines, having two fixed current probes A and B. It was found that skin effect is uninfluential in the frequency range adopted. Given the absence of natural or artificial disturbances in the signal (*e.g.*, electrode polarization and self potential), it was possible to perform very fast measurements with two operators only. Moreover, the use of a multiple dipole source configuration allows the calculation of the determinant of the apparent resistivity tensor. In the examples shown, this parameter detects the actual position of buried structures independently of the direction of the electric sources.

Key words *applied geophysics – archaeological prospecting – geoelectric – alternating current*

1. Methodological background

The main problems encountered with standard *dc* profiles are:

a) Difficulties in distinguishing a true signal from natural or artificial disturbances (*e.g.*, polarization of the electrodes or self potentials).

b) The number of people employed in field operations (at least 3 or 4).

c) A too long survey time for field work that normally, in archaeology, requires thousands of measurements.

To find the solution to these problems we consider the possibility of using *ac* fields and started planning suitable measuring instruments (Tabbagh, 1979; Cruciani *et al.*, 1989).

The Alternating Current Geoelectrical (ACG) method has its theoretical background in Maxwell's equations. Supposing that the investigated ground is a homogeneous and isotropic medium with magnetic permeability equal to that of free space and resistivity in the range of typical earth materials (say 10-10^6 $\Omega \cdot$ m), for current frequency up to 10^2-10^3 Hz, the displacement current can be ignored. For this reason the ACG method is a diffusive problem. In this case, the electromagnetic (*em*) field behaviour is regulated by the skin depth parameter δ

$$\delta = 500\sqrt{\frac{2\pi\rho}{\omega}}\ (\mathrm{m}), \qquad (1.1)$$

i.e. the distance at which the amplitude of the *em* wave is reduced to a factor 1/*e*. In eq. (1.1), ω is the angular frequency.

The skin depth, *e.g.* 140 m in a minimum 10 $\Omega \cdot$ m resistivity environment is much greater than the distances and depths involved in ar-

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Mailing address: Dr. Dario Monna, Istituto per le Tecnologie Applicate ai Beni Culturali, CNR, Via Salaria km 29,300, 00016 Monterotondo St., Roma, Italy; e-mail: monna@mlib.cnr.it chaeological prospecting, about 10-15 m in our case. For this reason, the ACG method at a fixed frequency follows the traditional rules of the direct current (*dc*) geoelectric method.

The field technique we adopted consists of taking a regular grid of voltage measurements inside a selected area for a fixed position of the energising electrodes outside the area.

In standard procedures the well-known scalar apparent resistivity parameter is used to arrange and interpret the collected data.

A drawback of the geoelectric prospecting based on the scalar apparent resistivity definition is that mostly for 3D investigations an anomaly pattern is obtained generally not fully conforming to the expected body geometry. In fact, the measured total electric field $\boldsymbol{E}$ and the primary current density vector $\boldsymbol{J}$ for a non-uniform half-space are, in general, not parallel. As suggested by Bibby (1986) and Bibby and Hohmann (1993), the most general presentation of geoelectric data is in the form of an apparent resistivity tensor $[\rho^a]$ as

$$\boldsymbol{E} = [\rho^a]\boldsymbol{J}. \tag{1.2}$$

When a survey is made using two current bipoles with different directions, the four tensor elements may be determined as follows (Bibby, 1986)

$$\rho_{11}^a = \frac{E_{11}\,J_{22} - E_{21}\,J_{12}}{J_{11}\,J_{22} - J_{21}\,J_{12}} \tag{1.3}$$

$$\rho_{12}^a = \frac{E_{21}\,J_{11} - E_{11}\,J_{21}}{J_{11}\,J_{22} - J_{21}\,J_{12}} \tag{1.4}$$

$$\rho_{21}^a = \frac{E_{12}\,J_{22} - E_{22}\,J_{12}}{J_{11}\,J_{22} - J_{21}\,J_{12}} \tag{1.5}$$

$$\rho_{22}^a = \frac{E_{22}\,J_{11} - E_{12}\,J_{21}}{J_{11}\,J_{22} - J_{21}\,J_{12}} \tag{1.6}$$

where the first index represents one of the two bipole configurations and the second one the vectors component (*i.e.* $x = 1$ and $y = 2$). Obviously, in order to measure the two components of the electric field with this procedure, the potential drops across two perpendicular dipoles must be collected in each node of the grid.

From the apparent resistivity tensor it is possible to calculate its determinant, which is rotation-invariant and thus independent of the direction of the electric field vector:

$$\rho_{\mathrm{Det}}^a = \det\,[\rho^a]^{1/2}. \tag{1.7}$$

The determinant apparent resistivity gives an *average* resistivity, which, as discussed in Bibby and Hohmann (1993), is better related to the shape and position of the inhomogeneities, eliminating the false anomalies arising from border effects near the electric discontinuities.

2. Experimental results

2.1. *The Sabine Necropolis of Colle del Forno (Montelibretti, Rome)*

In the Sabine Necropolis at Colle del Forno located in the Tiber Valley 30 km north of Rome, one area not yet excavated was chosen for testing the resolution power of the method described here above. The existence of a hypogeal *dromos*-chamber tomb was hypothesised by a previous geophysical prospecting (Bernabini *et al.*, 1985; Cammarano *et al.*, 1998, this volume). Figure 1 shows the typology of a Sabine tomb in the necropolis (Santoro, 1977).

The adopted measuring procedure can be summarised as follows. An *ac* source field was generated by two probes A and B injecting into the ground a current of 100 mA and frequency of 128 Hz. The potential drops were taken across a 0.5 m receiving dipole MN.

In the first experiment the line joining the current probes A and B was oriented in the N-S direction. The receiving MN dipole was moved with a sampling step of 0.5 m along parallel lines to the N-S direction. The distance between two consecutive profiles was also 0.5 m, the distance between A and B was 19 m and the dimension of the surveyed area was 9 m × 9 m. This first survey totalled 361 data that generated the apparent resistivity map drawn in fig. 2 in which a strong conductive

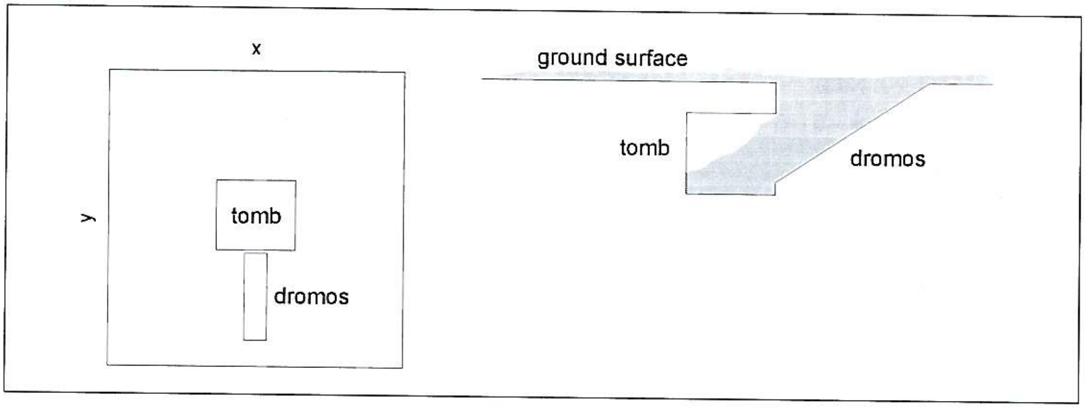

Fig. 1. Plan view and cross-section of the standard model of a *dromos*-chamber tomb in the Sabine Necropolis at Colle del Forno, Rome, Italy.

anomaly, perpendicular to the western border of the area, is very clear. Probably, this anomaly represents the corridor (dromos) of a chamber-tomb; the low resistivity values are due to the presence of very conductive materials filling up the dromos. Moreover, this structure seems to be connected with the higher resistivity zone located in the central part of the surveyed area. This second anomaly could be ascribed to the cavity of a tomb.

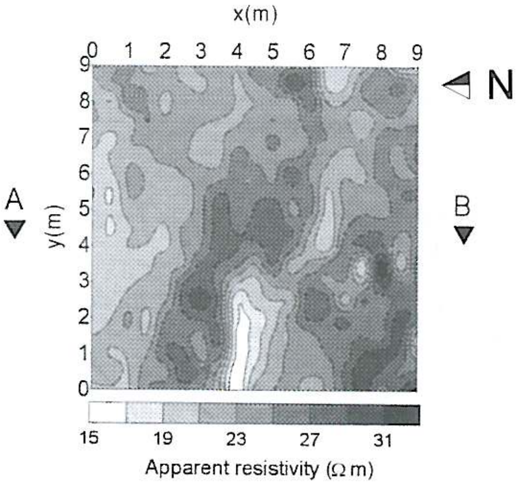

Fig. 2. Apparent resistivity map in a 9 m × 9 m area in the Sabine Necropolis of Colle del Forno (Montelibretti, Rome) with energising dipole in the N-S direction.

A second experiment was then carried out with the current probes A and B spaced as before across the survey area but along the E-W direction. The 0.5 m long MN dipole was also aligned in the E-W direction and moved every 0.5 m along parallel E-W straight profiles equispaced by a 0.5 m step. Again 361 measurements were processed to yield the apparent resistivity map shown in fig. 3. The presumed cavity now appears much better delineated by the apparent resistivity high in the central part of the map. The filled corridor is now singled out by the encircled resistivity low in the western side.

The comparison between figs. 2 and 3 shows how the electric field source pattern in the two experiments induces a different apparent resistivity distribution.

Using the tensorial approach (fig. 4) the dromos-chamber structure is very well evident.

We also studied the influence of the skin effect over the data. Measurements taken at 256 and 512 Hz gave the same results within the limits of the instruments used (0.1 mV sensitivity error). Moreover, measurements previously taken (Cruciani *et al.*, 1989) over another site of the Sabine Necropolis of Colle del Forno, at the frequencies of 500 and 5000 Hz, normally showed a discrepancy of 5% (fig. 5).

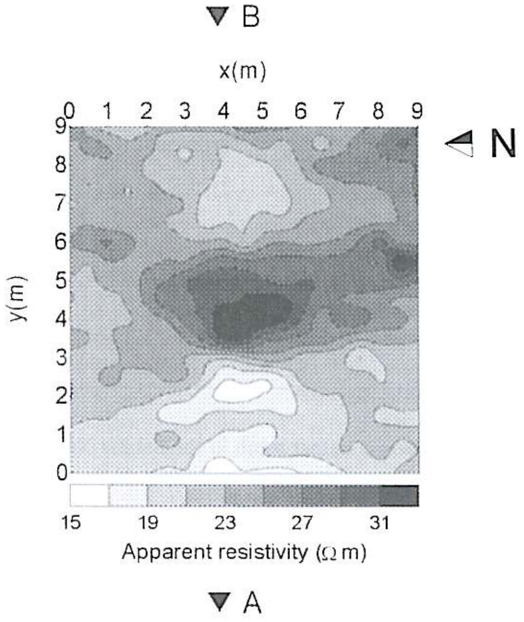

Fig. 3. Apparent resistivity map in a 9 m × 9 m area in the Sabine Necropolis of Colle del Forno (Montelibretti, Rome) with energising dipole in the E-W direction.

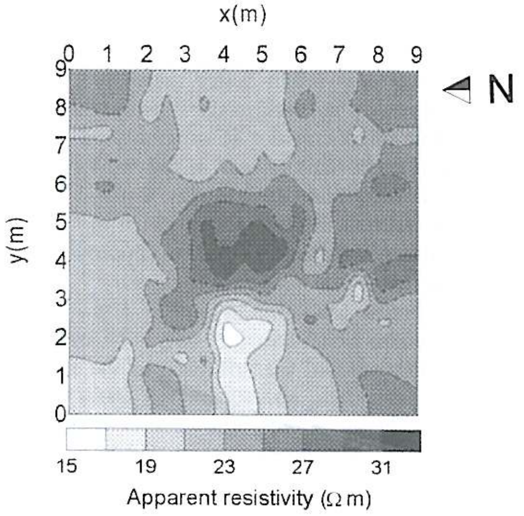

Fig. 4. Determinant map of the apparent resistivity tensor in a 9 m × 9 m area in the Sabine Necropolis of Colle del Forno (Montelibretti, Rome).

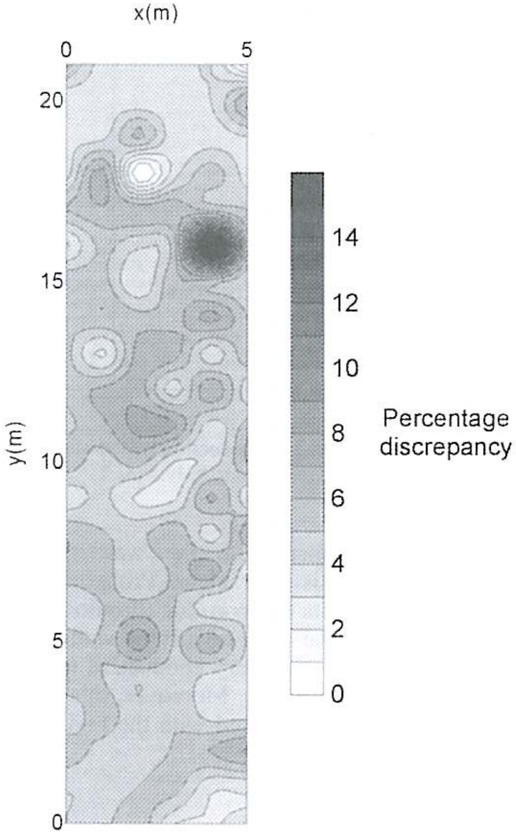

Fig. 5. Map of the percentage discrepancy between the potential difference measured at 500 and 5000 Hz within an area in the Sabine Necropolis of Colle del Forno (Montelibretti, Rome).

2.2. *The Etruscan settlement of Poggio Colla (Vicchio, Florence)*

The site of Poggio Colla is located in the Mugello, about 30 km northeast of Florence. This site is particularly important bacause it has undisturbed habitation layers that span much of Etruscan history, well-defined fortification walls, an extensive necropolis area, and the rare remains of an archaic monumental building, probably a temple (Warden *et al.*, 1996).

In order to test the resolution power of the method in a very difficult situation, a ACG prospection in the area of the probable temple

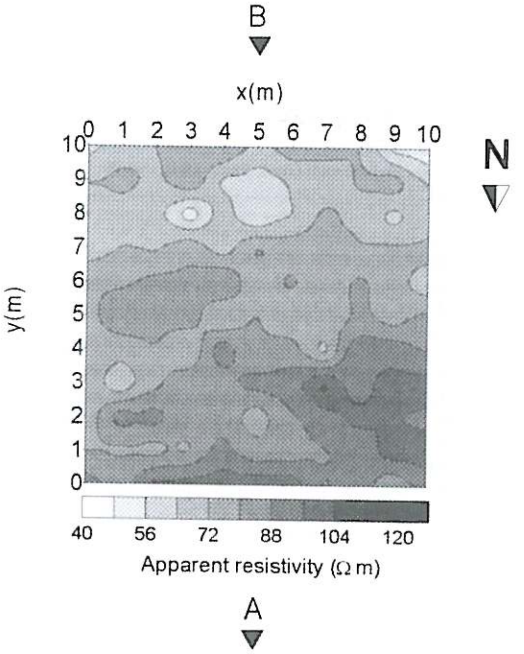

Fig. 6. Apparent resistivity map in a 10 m × 10 m area in the Etruscan settlement of Poggio Colla (Vicchio, Florence) with energising dipole in the N-S direction.

was performed: in fact, the wall remains in this site are sandstones in an weathered environment of same type. Thus, low resistivity contrasts were expected.

As in the previous case, a survey area of 10 m × 10 m was investigated with two field configurations: in the first one, the current probes A and B were at a spacing of 28 m along a line in the N-S direction and located symmetrically on one and the other side of the area. The receiving MN dipole was also moved with a sampling step of 0.5 m along parallel straight-lines in the N-S direction. The distance between two consecutive profiles was also 0.5 m. The 441 collected data are reported in the apparent resistivity map drawn in fig. 6.

Instead, fig. 7 shows the apparent resistivity map relative to the W-E polarization field. The first evidence in comparing figs. 6 and 7, is the great disagreement between the two maps. This is probably due to the above invoked complex situation, for which a serious source dependence in the apparent resistivity behaviour exists. For this reason a source-invariant as the determinant of the apparent resistivity tensor seems again the best parameter to describe such a situation. Figure 8 shows the apparent

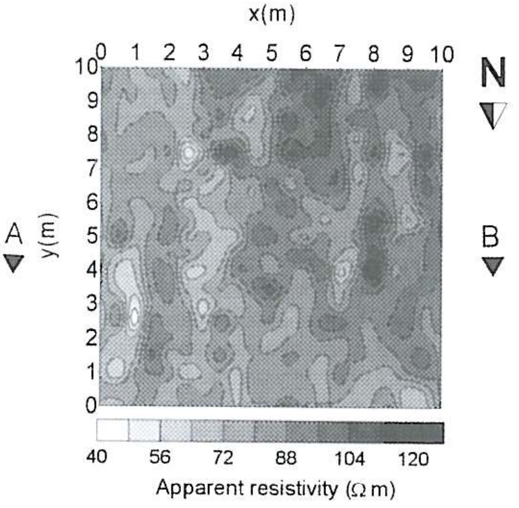

Fig. 7. Apparent resistivity map in a 10 m × 10 m area in the Etruscan settlement of Poggio Colla (Vicchio, Florence) with energising dipole in the E-W direction.

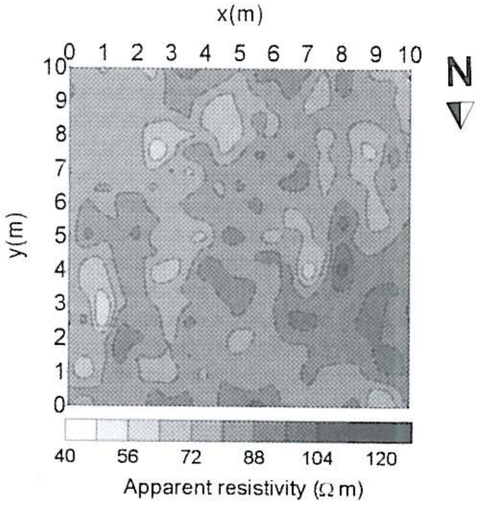

Fig. 8. Determinant map of the apparent resistivity tensor in a 10 m × 10 m area in the Etruscan settlement of Poggio Colla (Vicchio, Florence).

resistivity determinant map in which it is possible to identify some high resistivity anomalies, that, based on their dimensions, are likely to be ascribed to buried walls.

3. Conclusions

The *ac* resistivity method was applied in two sites of archaeological interest. The main results of the work are:

a) No skin effects were present in the frequency range adopted, hence traditional *dc* rules are still applicable.

b) The true signal is not affected by natural or artificial disturbances.

c) The survey time and the number of people employed in field operations were halved.

Finally, using a multiple bipole source the determinant of the apparent resistivity tensor is demonstrated to be a good parameter for discriminating archaeological structures. Moreover, the electrode array here adopted, where the A and B probes generating the primary field are kept in the same place, allows possible development in the field of the tomographic inversion (Patella, 1997).

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