BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXIV, N. 134-135 - JUNE-SEPTEMBER 1992

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EM-VLF SOUNDINGS ON THE EASTERN HILL OF THE ARCHAEOLOGICAL SITE OF SELINUNTE

Abstract. The electromagnetic VLF exploration technique, already employed in the search for mineral deposits, is used for geophysical investigations of the archaeological site on the eastern hill of Selinunte. Two areas, with a size of 90x90 m and 40x40 m, are detected. The application of the VLF method requires proper calibration and a careful study of the characteristics of the recorded signals. Planning the appropriate type of investigation, as well as interpretation for the results, needs preliminary information on the prevailing pattern of the structures and their inferred depth and composition. Although the studied area shows low signal levels, likely due to buried man-made artifacts, it is possible to highlight structures characterized by different conductivities at depths shallower thant 4-5 m. In the 90x90m area, the results allow inferences mainly on subsoil structure. A variation of the depth of the calcarenitic bed and its fracturing process is observed. The lateral variations of ground conductivity are likely ascribed to the filling of fractures with material coming from the cover. In the 40x40 m area, besides small anomalies of geological character, significant perturbations, probably associated with buried buildings, are found.

INTRODUCTION

The geophysical research program on the easternhill of Selinunte (Fig. 1) consisted in the application of new experimental techniques, among which VLF (Very Low Frequency) electromagnetic investigation.

As the VLF data acquisition process does not require galvanic contacts with the ground, it is also very fast over extensive structures needing a large area coverage and great detail. The measured signal is analyzed using some of its components. The interaction of the primary electromagnetic (EM) field with the underground sources of the anomalies is theoretically known for structures of simple geometrical shape. When a conductors is present, the total VLF field is elliptically polarized; the measured parameters are the angle of inclination (tilt) of the major axis of the ellipse and its ellipticity (i.e. the ratio between the major and the minor axes).

VLF instrumentations generally give digital measurements of the in-phase and in-quadrature components of the resultant vertical magnetic field, with reference to the intensity of the primary fields. The in-phase and in-quadrature components are proportional respectively to tilt and ellipticity.

EXPERIMENTAL TECHNIQUES

The EM-VLF method is suitable to detect conductive mineralized bodies with roughly vertical extension and not located too deeply (e.g. Paterson and Ronka, 1971; Phillips and Ri-

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Manuscript received January 15, 1992; accepted March 13, 1992.

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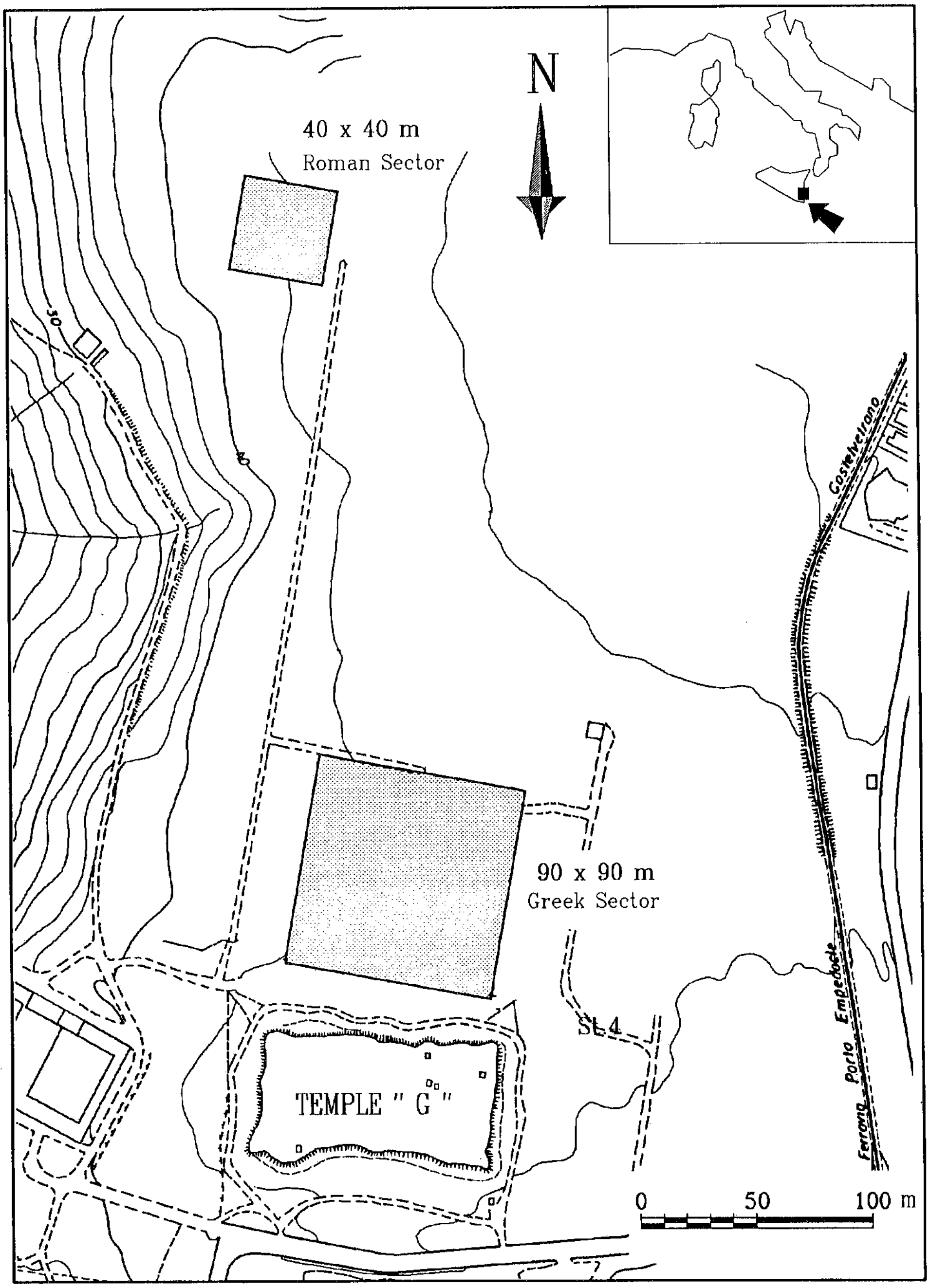

Fig. 1 - The eastern hill of Selinunte, showing the 90x90m and 40x40m sectors of the EM-VLF experiments.

chards, 1975; Fisher et al., 1983; Aina and Emofurieto, 1991). The method can be employed to search for buried structures, provided that there is appreciable conductivity contrast between the structural remnants and the enclosing medium, and that the geometrical conditions outlined above are satisfied (Ogilvy et al., 1991a). The measured signal is the resultant of the primary EM field and the secondary field due to underground induction phenomena.

In a homogeneous medium of very high resistivity, the primary field of the source is almost

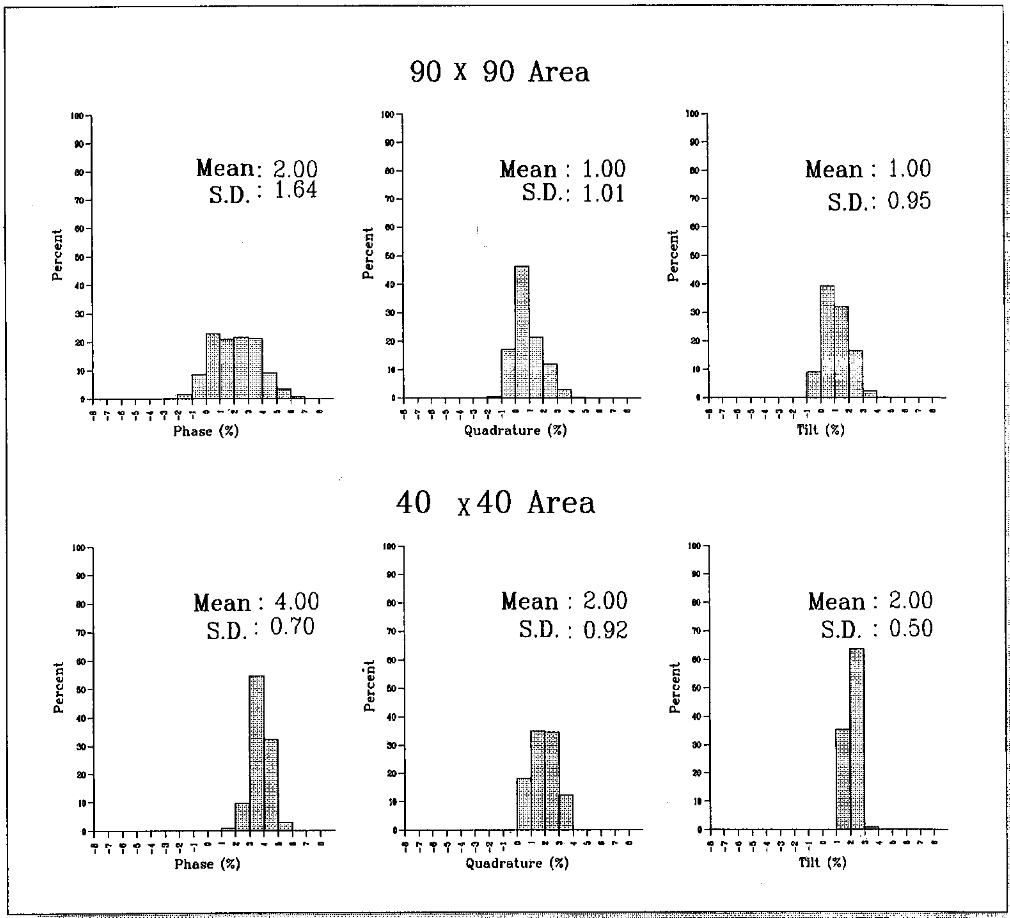

Fig. 2 - Statistical distribution of the in-phase and in-quadrature values in the 90x90m and 40x40m areas.

unaffected by perturbations; on the other hand, the presence of a conductive body with a vertical laminar shape produces induced currents, responsible for the secondary EM field. The resulting EM field is elliptically polarized and its elements can be determined from the parameters of the polarization ellipse (Saydam, 1981; Sinha, 1990).

In general, VLF exploration is carried out along profiles; the trend of one component or among different components along the profile provides us with indications on the underground conductivity pattern.

For the electromagnetic investigation of the eastern hill of Selinunte, we used a VLF OMNI-EDA instrument, which consist of a microprocessor system controlling the sensors, the transformation of the signals and the recording. The equipment operates within a 15 to 30 kHz range and can use up to three transmitting stations during the same cycle of measurement. The sensors, formed by three coils axes perpendicular to each other, measure the vectorial composition of the signal at some selected frequencies.

The signal is processed using: i) the in-phase and in-quadrature terms of the vertical magnetic component of the resultant, and ii) the tilt of the polarization ellipse for each frequency. The tilt is proportional to the dip of the polarization ellipse and is therefore related to the in-phase component. At the same time, we also obtain ancillary information such as the total intensity of the field which is an index of the quality of the measurement, its progressive number and the recording time. Initially, it is necessary to select transmitting stations with good quality

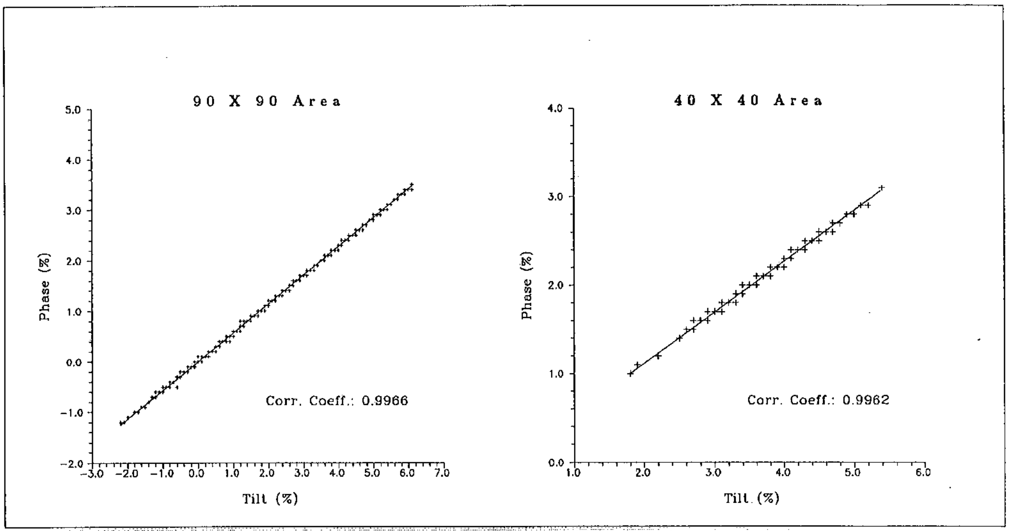

Fig. 3 - Correlation between phase and tilt in the 90x90m and 40x40m areas.

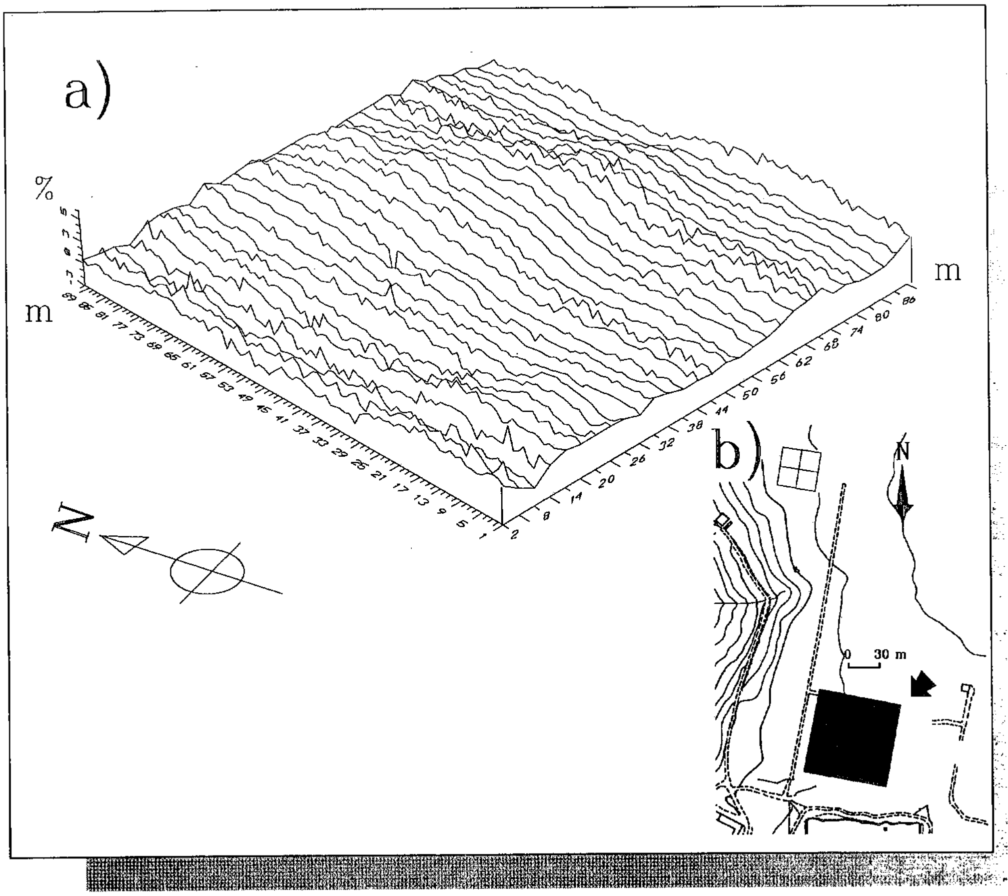

Fig. 4 - Profiles of the in-phase component for the 90x90m area.

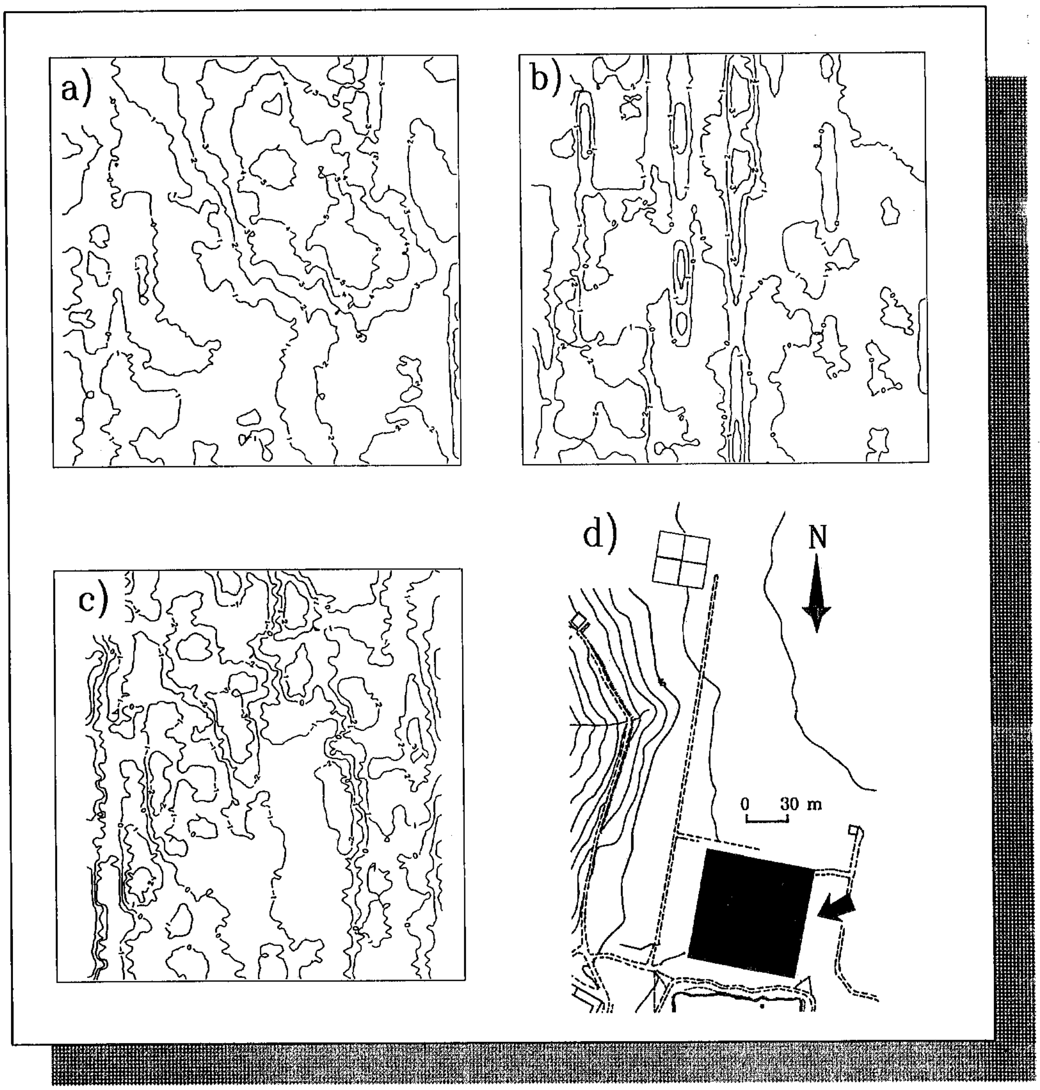

Fig. 5 - Bidimensional representation of the in-phase (a), in-quadrature (b), and Fraser's filtered phase (c) values in the 90x90m area.

signals, to determine their distribution with respect to the azimuth and the continuity of the transmission. The investigation can be carried out with measurement lines oriented towards the transmitting station or perpendicular to it. If many stations are available, simultaneous measurements along two perpendicular alignments can be performed. Of course, a specific orientation with respect to the structures should be maintained.

The two areas where we carried out our survey and which we refer to hereafter as the 90x90 m and 40x40 m areas, are located on the eastern hill of the archaeological park of Selinunte. The first of them occurs directly to the north of temple G; the second one is located about 300 m NNW of the same temple (Fig. 1).

From an analysis of the spectrum of the signals received in the zone under investigation, we selected the following frequencies: 16 kHz (Rugby-U.K.), 19.6 kHz (Oxford-U.K.) and 23.4 kHz (Rhauderfehn-D), all located in the north sector. They were used for all the recordings collected in this area. For both sectors a south - north orientation of the measuring profile was chosen.

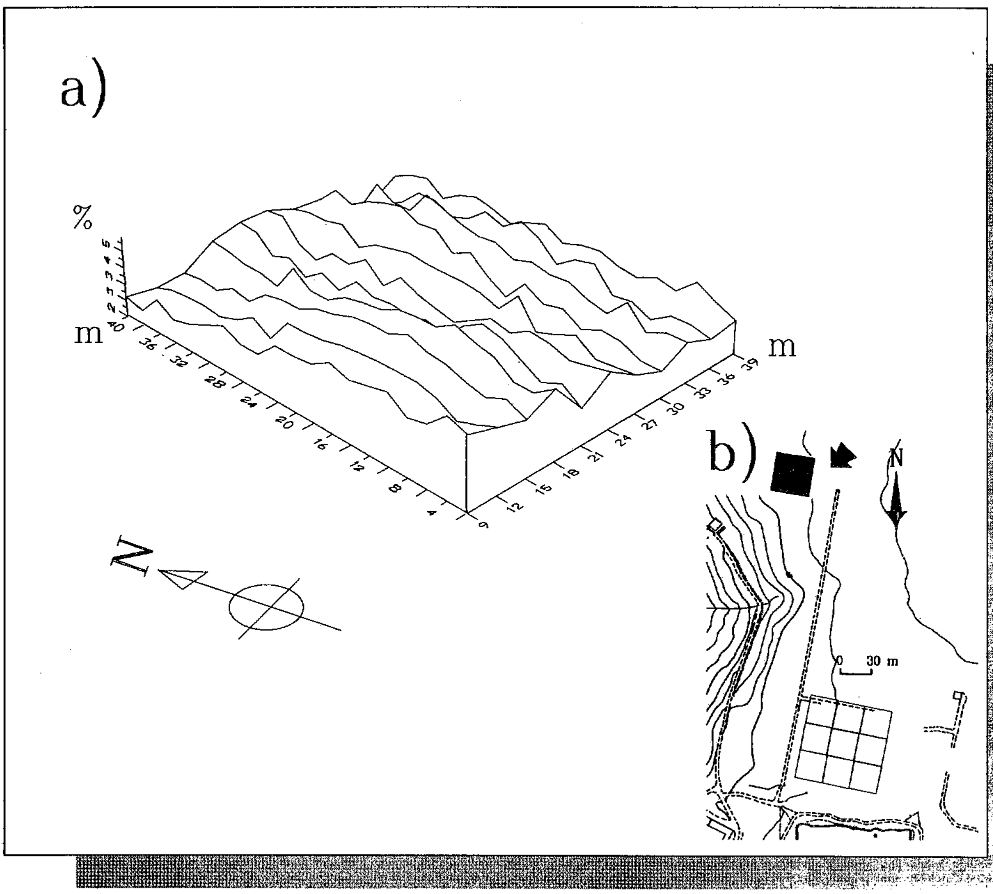

Fig. 6 - Profiles of the in-phase component for the 40x40m area.

The 90x90 m area was covered with 30 lines, each of them 90 m long, parallel to the NNE-SSW side of the same sector, and located 3 m apart, with measurements taken every meter (Fig. 4). In total, 2700 measurement stations were surveyed for each of the selected frequencies.

The 40x40 m area was covered with 11 profiles located 3 m apart and with measurements taken along the profiles every two meters (Fig. 6). In the middle part of the 90x90 m area, the survey was carried out on a 30x30 m sector with E-W oriented profiles, i.e. perpendicular to the former setup. The lines along these profiles were 2 m apart, and measurements were taken every meter (Fig. 8).

DATA PROCESSING AND MAPPING

As the reception frequency characterized by the best continuity and reliability was that of 16 kHz, the subsequent processing refers to this source. The other frequencies, when usable, showed a similar behaviour with significant differences only in the absolute values.

From a statistical point of view, the amplitude and the distribution of the values measured for the main components (phase, quadrature and tilt) were determined first. In Fig.2, the results of the three components for the 90x90 m and 40x40 m areas at 16 kHz are presented. The distribution of the in-phase and tilt components are similar. The analysis in Fig. 3 shows a very high (0.996) correlation coefficient between these two parameters. A significant correlation between in-phase (or tilt) and quadrature does not appear.

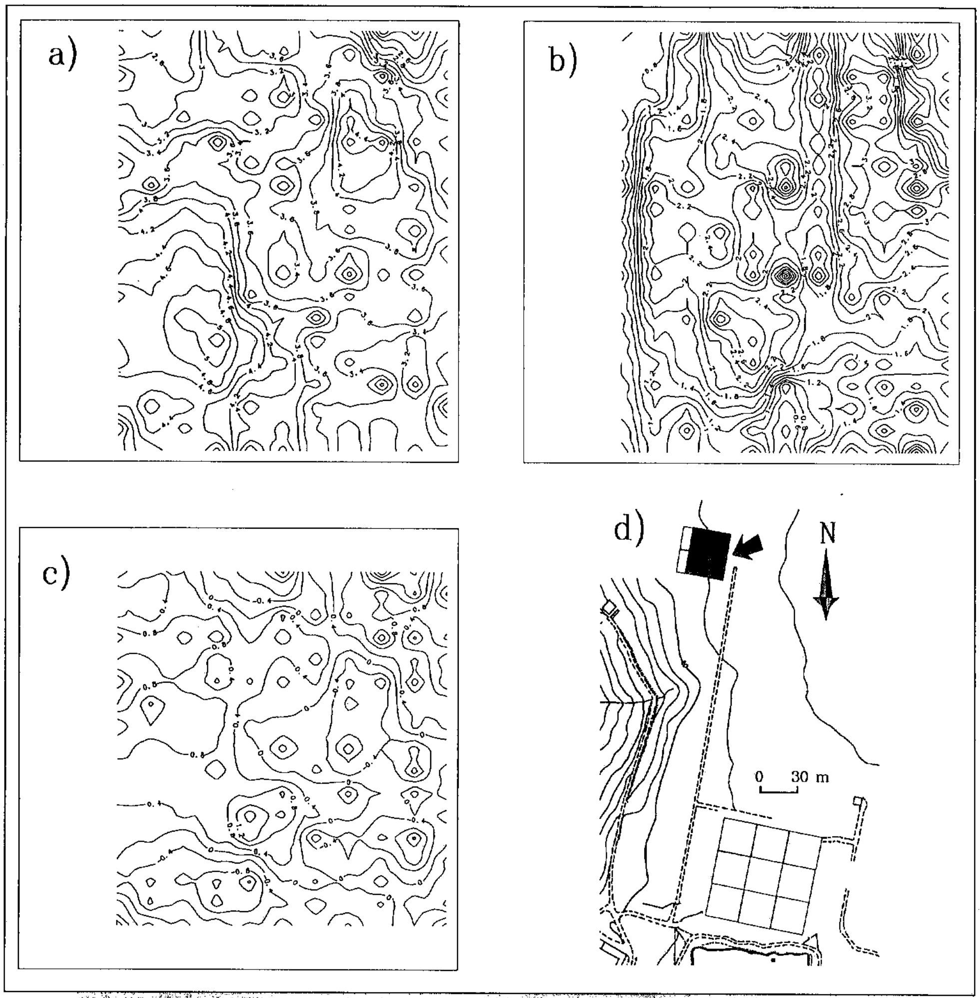

Fig. 7 - Bidimensional representation of the in-phase (a), in-quadrature (b), and Fraser's filtered phase (c) values in the 40x40m area.

A comprehensive overview of the profiles related to the in-phase component of the 90x90 m area is shown in Fig. 4. An appropriate interpolation of this data set can be mapped. In Fig. 5, the in-phase (a) and in-quadrature (b) components at 16 kHz are shown for the 90x90 m area. Although the values of these components are rather low, the in-phase component shows a quite wide anomaly in the NE sector, while the in-quadrature component exhibits only NS alignments. The digital filter with four non-zero coefficients, proposed by Fraser (1969), was applied to the in-phase component. This procedure transforms, by means of a differential operator, zero-crossings into peaks, and reduces noise by a low-pass smoothing operator. This attempt at eliminating the geological noise may however also attenuate the signal of interest. Fig. 5c shows the results of this procedure for the in-phase component.

A similar procedure was applied to the 40x40 m area; Fig. 6 shows the profiles of the in-phase (a) component of the area. The medium value of the in-phase and of the in-quadrature components always remains low; furthermore, in the quadrature component, a N-S alignment is observed, possibly as a result of the interpolation and contouring. Fig. 7c shows the distribution of the phase, filtered with Fraser's procedure.

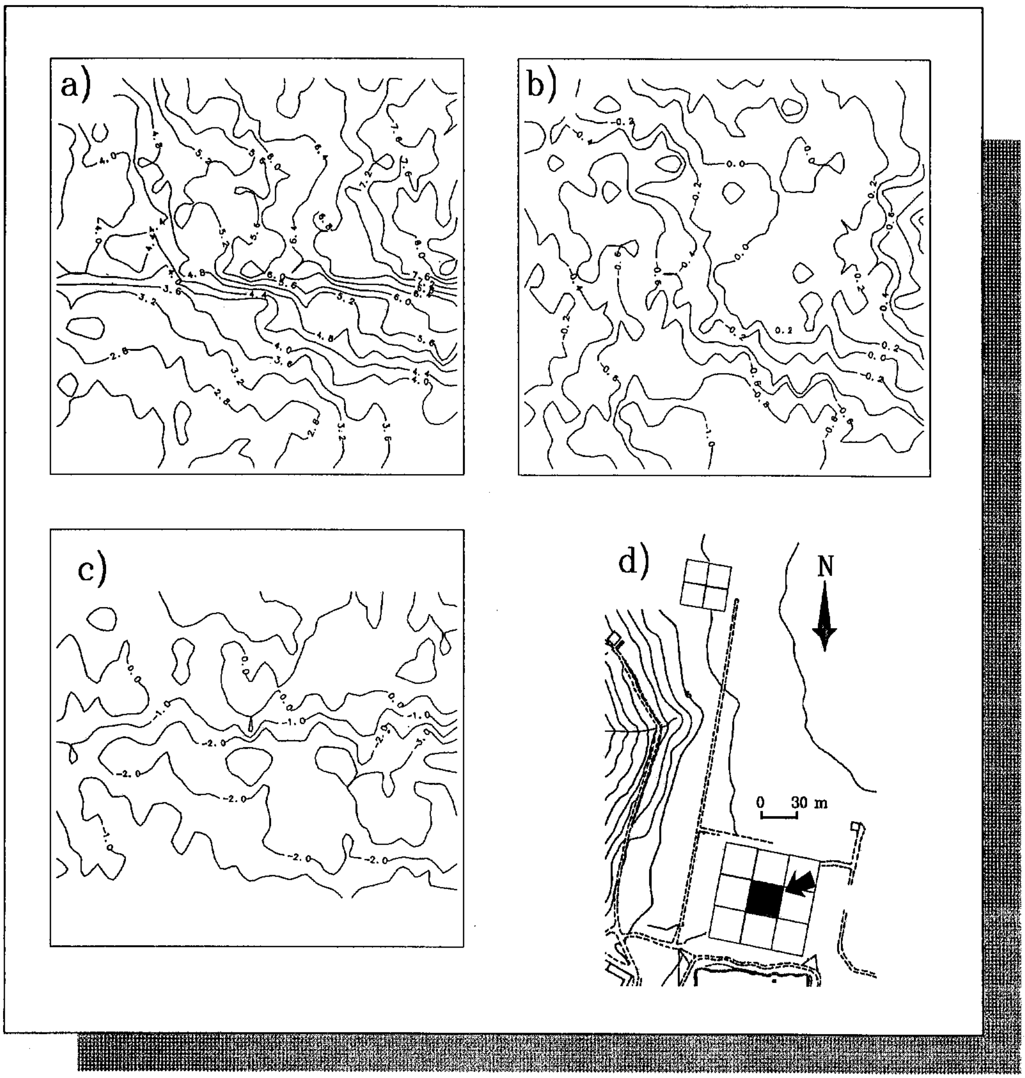

Fig. 8 - Bidimensional representation of the in-phase (a), in-quadrature (b), and Fraser's filtered phase (c) values in the 30x30m sector of the 90x90m area.

The influence of the direction from which the main signal was originated has been studied in the central part of the 90x90 m sector (Fig. 8). The survey was carried out on E-W oriented profiles, using the frequency of 16 kHz. Figure 8 shows the patterns of the components, which are in-phase (a), in-quadrature (b), and in-phase filtered, according to the procedure proposed by Fraser (c). A strong gradient oriented in a N-S direction can be observed for the in-phase component. This is much stronger than in the remaining part of the 90x90 m area and may be due to a variation in the thickness of the cover (Bozzo and Merlanti, 1992).

CURRENT DENSITY PSEUDOSECTIONS

The VLF data can be interpreted by applying a filter to the resulting magnetic components. An interpretative pattern proposed by Karous and Hjelt (1983) can be used to generate pseudosections of the current density distribution by filtering the in-phase component. Such pseudosections give information on the current concentrations at different depths and, therefore, on the position of conductive structures in the subsoil. This technique of finite filtering is an

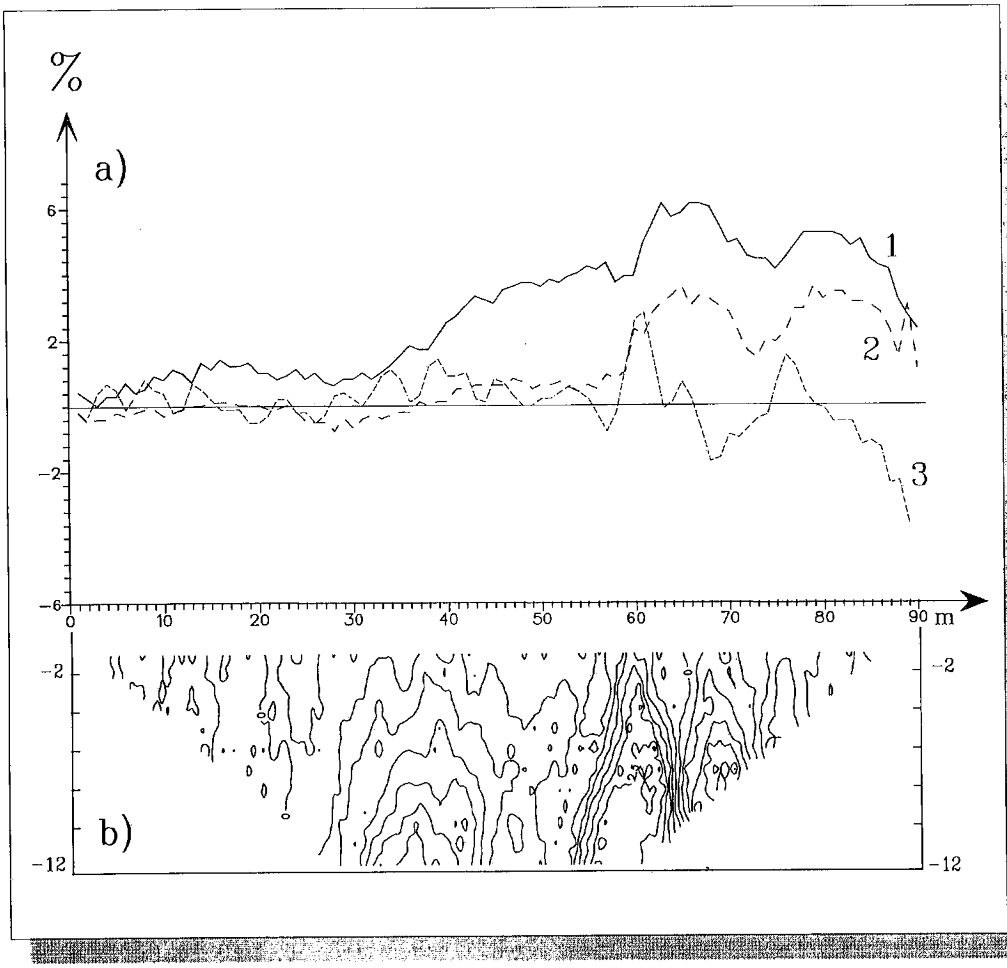

Fig. 9 - Pseudosection of the distribution of the current density Karous filter to the 12th level. The behaviour of the in-phase (1) and in-quadrature (2) components and the first level Fraser filtering (3), are reported.

improvement on Fraser's (1969) filter, and is directly correlated with magnetic fields generated by the current flow in the ground. By using a discrete filter for the real (in-phase) VLF component, values of equivalent current densities can be obtained at constant depths for the measured magnetic field. This technique gives a complementary method for determining the depth; in practice, the position of the structures an/or the conductors within the subsoil cannot always be derived from the distribution of the current density (Ogilvy and Lee, 1991b).

Fig. 9 presents an example of a pseudosection obtained by the application of a Karous filter down to the 12th level on the 50th profile located in the central part of the 90x90 m area. It clearly shows lateral variations in the distribution of the current density. The sign of these variations depends upon the direction from which the signal comes, the direction of the profile and the attitudes of the buried structures characterized by different conductivities.

A correlation between the pseudosections derived from the Karous filtering on all the profiles is proposed in Figure 10a. The filter output supplies significant results only in the central part of the 90x90 m area. The location of the positive maxima, ascribed to a conductivity minimum, as well as those of the negative maxima, corresponding to a conductivity maximum, were derived for each pseudosection. Their distribution shows a systematic pattern, revealing strong lateral variations in the current density, mainly in the NE and SW sectors. A qualitative tridimensional representation of the discontinuities is also shown in Fig. 10b, in which the vertical axis is assumed to be proportional to conductivity increasing upwards.

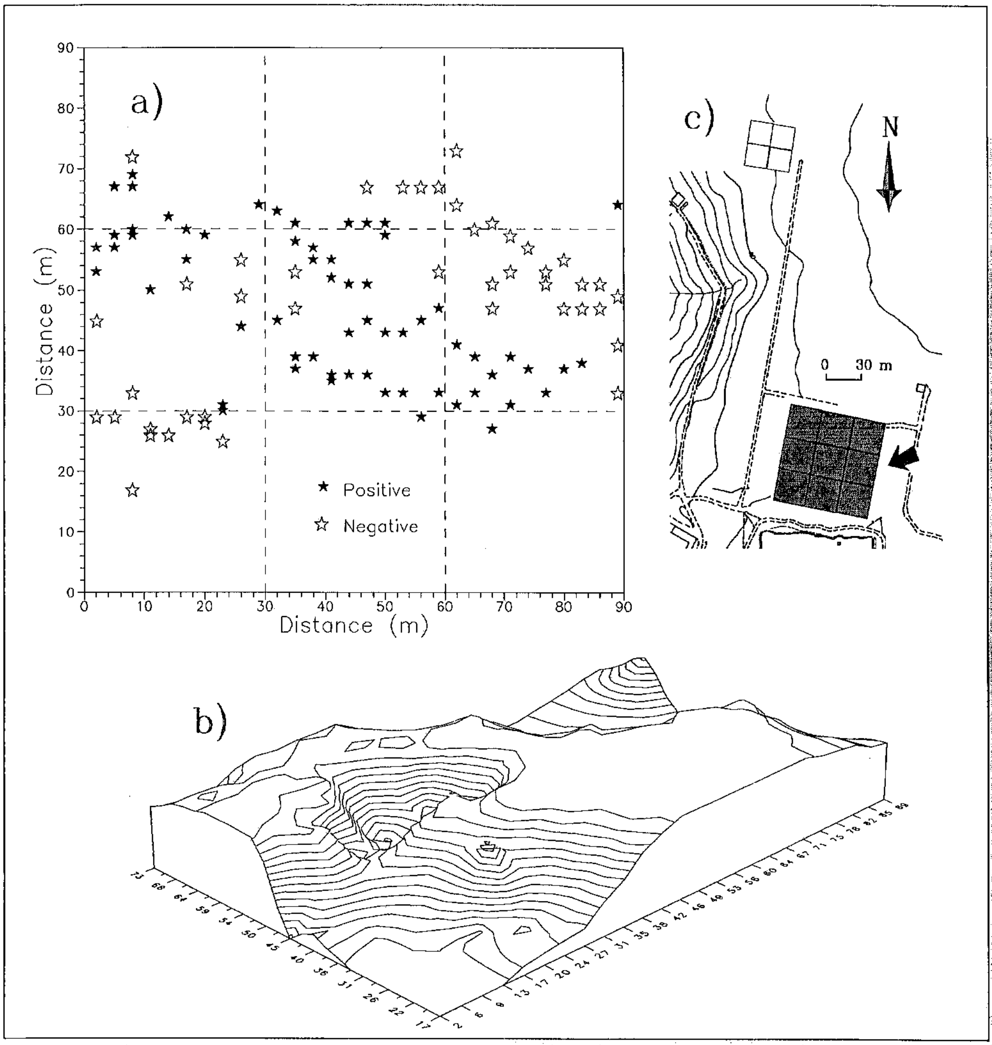

Fig. 10 - Bidimensional (a) and tridimensional (arbitrary scale) distribution (b) of the main results obtained from the Karous filtering of all the profiles in the 90x90m area.

DISCUSSION

The systematic application of the EM-VLF technique in the surveyed areas shows that the interpretation of the data is strongly affected by geological noise. Knowledge of even approximate locations of the targets requires an arbitrary selection of directions of the profiles and transmitting stations.

The low resistivity of the subsoil causes a decrease of the depth of investigation (skin depth). Also the low resistivity contrasts do not allow a sharp resolution of the anomalies. This appears from Fig. 2 in which a range of only a few percent is distributed around average values close to unity, with a clear unimodal shape and a low dispersion. In this context, the in-phase component shows more significant values with respect to the quadrature or the tilt. The in-quadrature component, which is more sensitive to the effects of the secondary induction, shows very low values in all cases. As one can describe the general pattern of measurements through one component only, in our case it seems convenient to use the in-phase component. A general examination of this component for the 90x90 m area shows a slight increment in percentage along the NE-SW direction (Fig. 5a). This may suggest a local decrease in the thickness of the calcarenitic slab or the presence of a weakly conductive buried structure near the area under investigation. The in-phase component, filtered using the procedure proposed by Fraser, confirms the presence of anomalous "islands" aligned along the N-S direction (they have already been highlighted using the in-quadrature component); these anomalies seem to suggest irregular lateral variations in the calcarenitic sheet and are characterized by a weak conductivity contrast (Figs. 5b and 5c).

Fig. 7a of the 40x40 m area shows the presence of geological noise due probably to small sources in the overburden. Signals with higher wavelength are observed mainly in the SW quadrant of the sector and also in the NE zone. The quadrature (Fig. 7b) and Fraser filtering (Fig. 7c) show a better alignment and lateral variability in the conductivity of the subsoil. The extent of the anomaly seems to rule out the presence of wall structures.

Fig. 8, which refer to the central part of the 90x90 m area, is more detailed and shows more intense variation along the EW direction with respect to the corresponding values measured in the 90x90 m area (Fig. 8a). The patterns of the quadrature and the Fraser filtering (Figs. 8b and 8c) confirm the existence of conductivity variations in the ground: they are not aligned and do not show any specific structures.

The pseudosections of the 90x90 m area, related to the in-phase component (Fig. 10a), show on overall non-random distribution. So, in the eastern part, a well-defined alignment of negative values of equivalent currents can be correlated farther to the south to a band of positive values of equivalent currents. As the proposed model highlights only anomalies associated with a certain number of levels, the discontinuity shown by the filtering is probably due to a calcarenitic horizon located just beneath the soil cover. The calcarenite, only a few meters thick in this area, was likely affected by widespread fracturing and subsequently filled with overlying material. Therefore it is very speculative to ascribe these alignments to man-made relicts.

Finally, this work shows that the application of VLF techniques in archaeological surveys can be very useful when it does not suffer from a reduced resolution of the structures due to a limited vertical extension of the buried bodies or small resistivity contrasts.

Aknowledgments. The Authors are grateful to Giorgio Caneva, Silvia Lombardo and Marco Gambetta for technical collaboration during data acquisition and graphic editing. Thanks are due also to Prof. Antonio Elena for thoughtful discussion.

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