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VLF prospecting: observations about field experiments

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Abstract
The VLF-EM prospecting technique is currently applied to various topics, *e.g.* archaeological and hydrogeological surveys, evaluation of environmental impact and monitoring of active volcanic areas. We are now suggesting a critical re-examination of a commonly accepted hypothesis, which has not been confirmed experimentally. In particular, we have investigated: the role of topographic irregularities on the measurement of the analyzed components; the coupling of data derived from different sources; the correlation between some components of the resulting field; the relationship between non-linearity in the signal transmission power, meteorological perturbations and scatter of measurements; the effects of conductive covers and finally the influx of the orientation of the sensors on the polarity of the measured components.

Key words *applied geophysics – VLF-EM prospection – environment – electromagnetism*

1. Introduction

As already known, measuring the intensity of radio waves is one of the oldest electromagnetic methods of exploration geophysics (*e.g.* Cloos, 1934). Of course, the intensity of the field measured during the exploration was influenced by some factors not related to the local geology. The availability of powerful transmitters operating in the 15-30 kHz band provided the VLF-EM technique with an operative standard for exploration geophysics in non-conductive environments.

The electromagnetic primary field generated by VLF transmitters propagates within a spherical wave guide, between the Earth's surface and the lower ionosphere. At a distance of about 100 km from the source, the magnetic component is roughly horizontal and perpendicular to the azimuth of the source; in the presence of a conductor its penetration in the subsoil generates a secondary field that interacts with the primary one. Thus, a resultant field, controlled by the electrical structure of the ground, is measured. This field is elliptically polarized and the characteristics of the secondary field can be referred to the parameter of the polarization ellipse. In particular, a tilt τ (inclination of the major axis) and an eccentricity $\varepsilon = b/a$ (*i.e.* the ratio between the minor and major axis) can be determined. Moreover, since the intensity of the secondary field is always less than that of the primary field, we can write (see *e.g.* Saydam, 1981; Sinha, 1990a)

$$\tau = R_e / H_p \tag{1.1}$$

$$\varepsilon = I_m / H_p \tag{1.2}$$

and therefore, the in-phase component R_e and the in-quadrature I_m components, normalized with reference to the main field H_p, can be evaluated.

Our Scintrex Eda-Omni instrumentation supplies the in-phase and in-quadrature components, normalized to the main field, together with complementary information, such as the intensity of the primary field and the tilt angle τ of the polarization ellipse.

Both electrical and magnetic components can be utilized in VLF geophysical prospecting. However, only the magnetic component *H* is currently used, since it is easier to calculate. In fact the vertical H_z component is analyzed, since it is generated only by induction phenomena, because the main field H_p lies almost in the horizontal plane.

The maximum effective depth reached by an electromagnetic wave, in relation to the frequency of the transmitter and the electrical resistivity of the medium, is called «skin depth».

2. A comparison between measurements at different frequencies

For an electromagnetic wave propagating vertically downwards, in an isotropic half-space, we have (see *e.g.* Sharma, 1986)

$$S = 503.8\,(\rho/\omega)^{1/2} \qquad (2.1)$$

where S is the skin depth in meters, ω the frequency (in Hz) of the source and ρ the resistivity (in ohm*m) of the medium.

Although the frequency of the VLF primary field varies between 15 and 30 kHz, for a given resistivity the difference between the maximum and minimum values of the skin depth is less than 20%. Thus signals at different frequencies can be utilized for the exploration of a subsoil with a similar thickness, provided that the azimuth of the location of the corresponding sources is consistent in relation to the measuring station. In this case, the information coming from different frequencies can be compared and a variation of the intensity of the resultant is ascribed only to the modified pattern of the system formed by the conductor, profile of measurement and direction of maximum intensity of the VLF magnetic component.

An experimental check of the above situation is illustrated in fig. 1, showing simultaneous measurement of the in-phase and in-quadrature components from the transmitting stations, at 16.0 kHz (Rugby, U.K.) and 19.0 kHz (Oxford, U.K.), with an almost identical

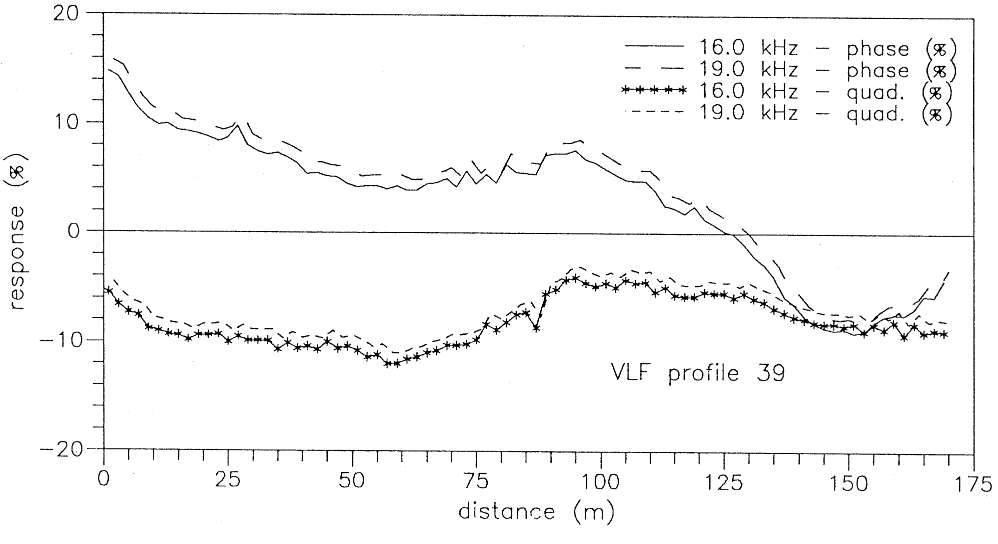

Fig. 1. A comparison between different frequencies (in-phase and in-quadrature component), received at two stations with different originating azimuths (from hydrogeological prospecting at Bonassola, La Spezia, NW Italy).

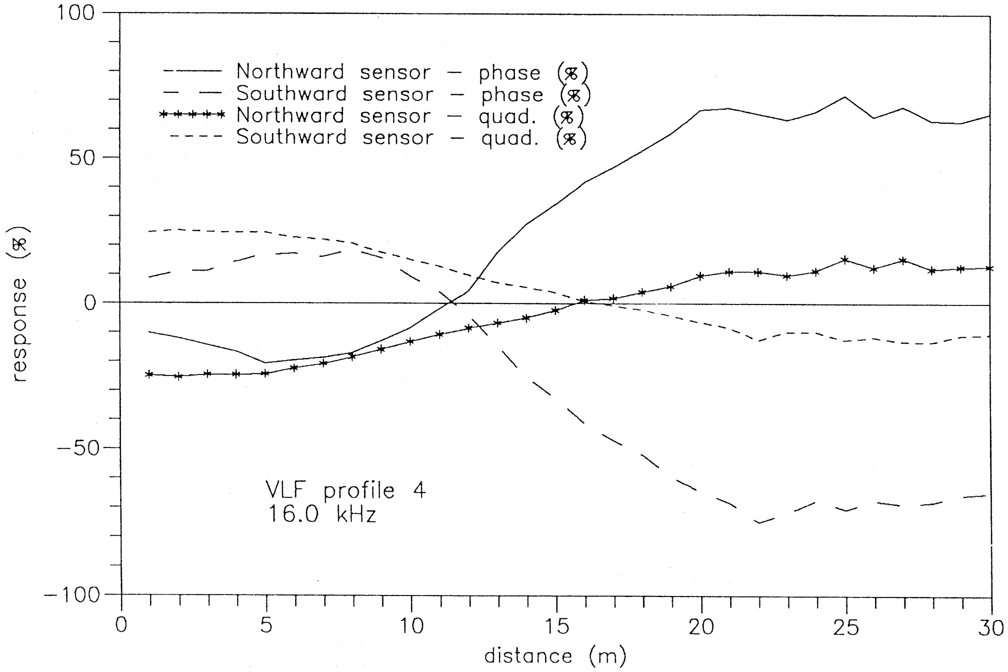

Fig. 2. The polarity of VLF signals, as a function of the orientation of the source (from prospecting on an active lava tube, Etna volcano, S Italy).

arrival azimuth. The behaviour of the two signals coincides and this allows experiments to be continued on the ground, also when one transmitter is interrupted.

Further experimental results show that for VLF signals with similar arrival azimuths there is a certain kind of «changeability principle». This leads to an increase in the temporal interval utilizable to take measurements.

3. Polarities in VLF measurements

Within a set of field data, the direction parameter is defined as the angle between the primary field and the sensor. This parameter makes it possible to verify the orientation of the sensor during the measurements along the profile. Such a control is requested on an irregular soil, where the trim of the apparatus can hardly remain constant. For changes of direction up to ± 30°, the signal variations remain negligible; but for greater changes the measurements are no longer comparable.

With the aim of checking some precautions in using VLF instruments, especially under particular conditions, we compared some experimental results with others available in literature.

A significant example of how the polarity of the signal depends on the orientation of the sensor is given in fig. 2. A profile, showing a strong anomaly on both components, was repeated by changing the orientation of the sensor by 180°. The behaviour of the in-phase and in-quadrature components is symmetrical; thus profiles are overlapped by reversing the sign of one data set.

To obtain the optimum answer, the measurement profile should be parallel to the lines of the primary field, *i.e.* perpendicular to the azimuth of the transmitter. During our surveys,

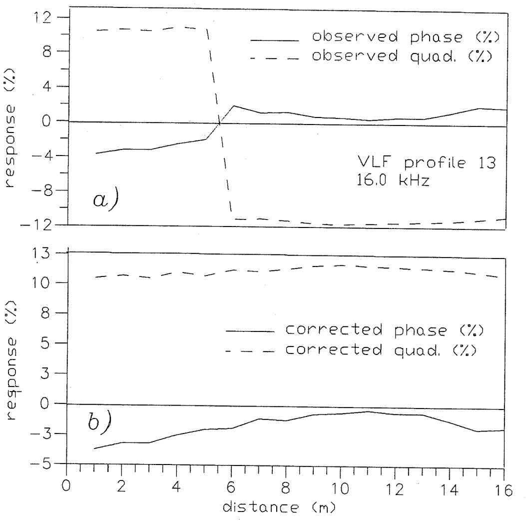

Fig. 3a,b. Measurements performed with orientation of the sensor near the critical direction: a) experimental data; b) corrected data (from prospecting in a mineralized sulphur area at Molini di Voltaggio, Alessandria, NW Italy).

we realized that often, for logistic reasons, it is impossible to operate under optimal conditions, so measurements are taken at any angle with respect to the station. However one must take care not to follow the critical orientation of + 45° from the direction of the transmitter, that is very sensitive to even small changes in the orientation of the sensor.

Figure 3a shows a VLF profile performed under these conditions. A small variation in direction at the 5 m progressive, led to a cross-over of both components; such a drawback can be eliminated by reversing the sign of the measured values (fig. 3b). This requires an a priori control, of the cross-over nature, which can be performed by graphing the value of the direction parameter along the profile. If the cross-over is coupled to a sign reversal of the direction parameter, it has no physical meaning and should be corrected, as in fig. 3b. If one operates simultaneously with many frequencies and the morphology of the profiles and direction at various frequencies are different, only those which show a direction reversal will be affected by an incorrect cross-over. This is the case shown in fig. 4, where the direction parameter, for the frequencies 16.0 kHz and 19.0

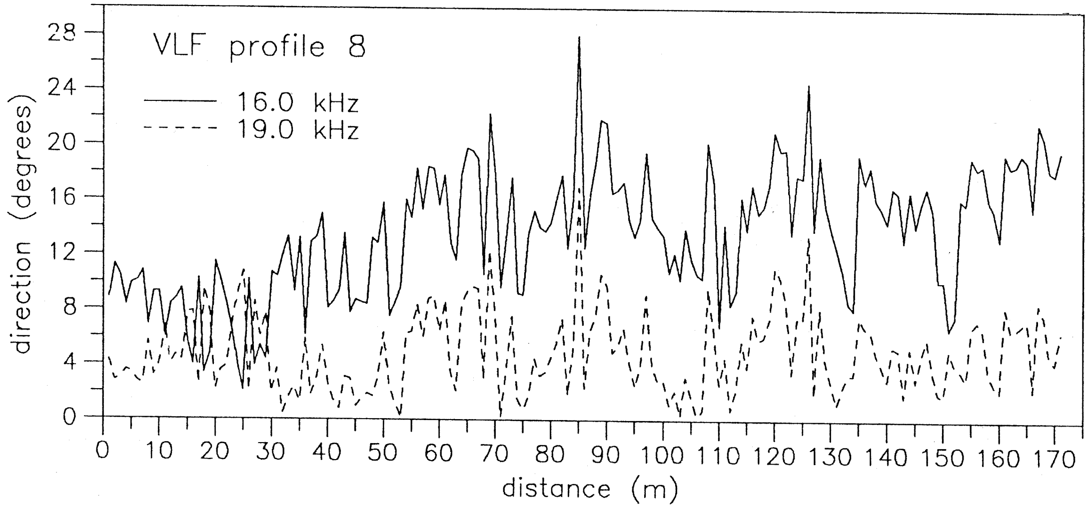

Fig. 4. A comparison of the angle between source and sensor, for simultaneous recordings of two frequencies (from prospecting for an environmental audit, Borghetto S.S., Savona, NW Italy).

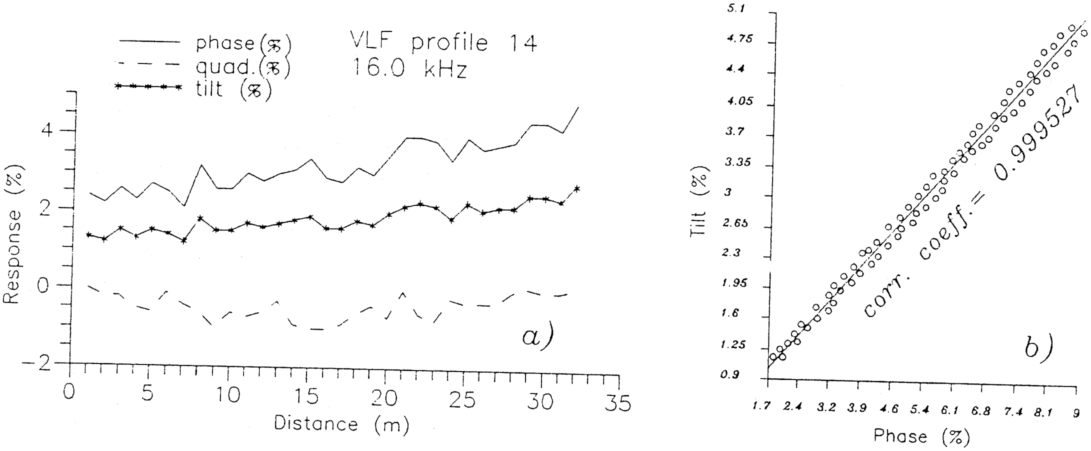

Fig. 5a,b. a) A comparative analysis of the in-phase and in-quadrature parameters and the tilt along a profile; b) correlation between phase and tilt in an area investigation (from an archaeological prospecting, Selinunte, S Italy).

kHz, is opposite between 0 and 35 m. The inversion occurs at a frequency of 19.0 kHz, whose parameters should therefore be corrected. The graph shows that the direction of the profile is critical only for a frequency of 19.0 kHz, even if both transmitters have similar arrival azimuths (see fig. 1).

4. Equivalence between different VLF parameters

The VLF instruments, as mentioned above, measure the behaviour of the polarization ellipse related to the interaction between the primary field and the ground. Useful parameters may include the tilt and ellipticity, the in-phase and the in-quadrature components and also the resultant total field. The in-phase component R_e and the tilt angle τ are often proportional (eq. 1.1): this feature, which is theoretically predicted, is experimentally confirmed.

Figure 5a reports the behaviour of the tilt (%), with the in-phase and in-quadrature components: the parallelism between the first two is evident, although it is related to a scale constant. Thus it is possible to operate only with the in-phase component, providing greater dynamic extension.

The statistical analysis was performed on many data sets, coming from different applications, which provide significant correlation indices. The example in fig. 5b refers to a sample of 15 profiles, each consisting of 30 measurements made in the archaeological area of Selinunte (Western Sicily) (Bozzo *et al.*, 1992). The very high correlation coefficient confirms the qualitative findings, which were formerly obtained from a smaller sample (fig. 5a).

5. The role of topography

Aside from the reduced dimensions and weight, the VLF instrumentation can also be utilized over an uneven topography. However, the uneven terrain generates distortions in the measured field, since it lacks the vertical incidence of the wave front on the ground surface. Such distortions are responsible for significant errors. Under these circumstances, it is necessary to evaluate and possibly eliminate the topographic effects from the ones arising from the buried structures to be investigated. A review of the techniques to reduce the topographic effect is given by Eppelbaum (1991); these techniques, however, are mainly based on an analytic development of models which often disagree with the survey data.

On the profiles performed in the direction of increasing height, the intensity of the in-phase and in-quadrature components generally show an apparent increase, and the contrary occurs in the direction of decreasing height.

Moreover, the topographic effect varies with the dip of the possible conductor: if the latter is vertical, the effect of the topographic dip only causes a shift in the point of flexion (Baker and Myers, 1980), while the morphology of the anomaly remains unchanged. The effect may be quite marked for inclinations from the vertical greater than 60° and topographic slopes greater than 15°. The experiments conducted using different methods, as proposed by Eppelbaum (1991), showed that the topographic correction of Eberle (1981) is satisfactory; thus the amount of the correction *dR* (%) for the in-phase and in-quadrature components is given by

$$dR = \theta \; (\sin \alpha / \sin \beta) \qquad (5.1)$$

where θ is the topographic slope, α the angle between the geological strike and the measurement profile, β the angle between the geological strike and the direction of maximum intensity of the magnetic field.

Optimum conditions correspond to $\alpha = 90°$ and $\beta = 90°$.

If the experimental conditions approximate the ideal ones, the relation (5.1) becomes

$$dR = \theta$$

which corresponds to the relationship of Baker and Myers (1980)

$$dR = K\theta$$

If the topography is irregular the correction is more important because the final trend of the profile could be very different from the measured one. Unfortunately the proposed method is effective only in case of monotone slope; otherwise the sign inversion of the value of slopes gives rise to anomalies of interference that need another kind of analytical correction. Nevertheless, topographic profiles with regular slopes can be considered monotone and so it is possible to perform the proposed correction.

The example shown in fig. 6 refers to VLF prospecting performed in a hilly area. The topographic profile is reported together with those of the in-phase component. The measurements were made in the direction of increasing height; therefore the correction should be subtracted from the observed values. Since the topographic slope along the profile is monotone and regular, a mean value of the slope, of about 17%, was adopted and the corresponding value *dR*(%) of about 20 was applied to all measurements.

The behaviour of the in-phase component, corrected for topography, is also reported in fig. 6, where the trends, before and after corrections, concur.

This profile also shows the effect of a conducting body not developed vertically: the measured anomaly becomes asymmetric.

In the example of fig. 6, we can assume that the anomaly is centred over the 145 m progressive. By means of the diagrams of Baker and Myers (1980), derived from numerical simulations on models, we can ascribe to the source a depth of about 12 m and a dipping of about 60° in the direction opposite to those of the profile, *i.e.* towards the increasing heights.

On the basis of the drilling performed in this area, the conductor appears to correspond to water contributions confined in sub vertical fractures, whose top lies at a mean depth of 10 m. This agrees with the profile interpretation.

The true location of the source along the profile can be determined by taking into account the effect caused by the dip of the conductor from the vertical (asymmetry of the in-phase curve with the greater amplitude on the immersion side of the conductor), as well as those ascribed to the topographic slope (shift of the cross-over point with the zero in the «up-hill» direction and distortion of the signal amplitude).

With our approach the above mentioned topographic correction can only compensate for

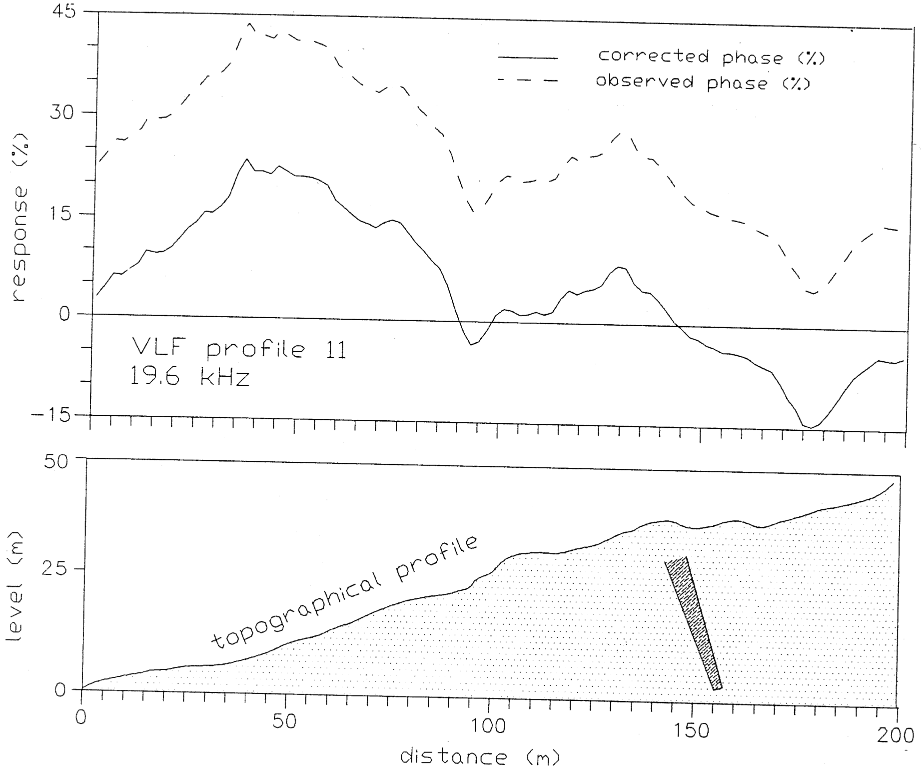

Fig. 6. An example of topographic correction applied to the in-phase component on an up-hill profile (from hydrogeological prospecting at Bonassola, La Spezia, NW Italy).

the vertical shift of the intensity, whereas the horizontal shift can be evaluated on the basis of the theoretical diagrams of Abdul-Malik *et al.* (1985).

In our case (a sub vertical conductor and a local slope of about 17°), there is a shift of about 1 m in the up-hill direction.

6. VLF primary field variations

The time and space variations of the VLF primary magnetic field may affect the interpretation of VLF data. The time variations can be recorded at a base station and utilized for corrections. This technique should be applied in airborne and ground VLF measurements when the value of the total resultant field is utilized.

However, for a wide investigation area, the time variations cannot be simply correlated. The behaviour of the time and space variations of the primary field over great distances and their implications in airborne prospecting are described by Vallée *et al.* (1992a); the variations of the intensity of the primary field are studied theoretically on the basis of radio wave propagation models. These models are based on the hypothesis of uniform conductivity of the upper layers of the Earth and a stratified ionosphere. Direct waves, *i.e.* transmitted by the ground, and waves reflected by the ionosphere, contribute to the total field. The EM ground wave prevails up to a distance of about

400-500 km from the transmitter; beyond this distance, the reflected waves become predominant and the total field becomes steady. The phase difference between the two contributions decreases with an increase in distance from the transmitter. If transmitting stations at distances greater than 500 km are used, such effects are negligible. This occurs in our experiments, where ground measurements are made over a not too large area and transmitting stations are located at a distance greater than 1000 km.

The irradiation characteristics of the transmitters also control the intensity of the primary VLF field. The main causes of instability of the primary VLF field are changes in transmission power, however changes in the propagation of the radio waves, related to geomagnetic activity, may also play a role (Vallée *et al.*, 1992b). Therefore, changes in the intensity of the VLF primary field during prospecting may occur.

Normalization of the in-phase and in-quadrature components of the field, with reference to the primary field at the same time, is sufficient to eliminate this kind of anomaly. However a good instrument must measure the total field too. This allows the signal level and the minimum instrumental one to be compared.

The simultaneous recordings of two transmitters, *i.e.* 19.6 kHz (Rugby, U.K.) and 23.4 kHz (Rhauderfehn, D), showing remarkable fluctuations of the total field, are reported in fig. 7. The 19.6 kHz signal, in spite of its drop at 644 min time, can be processed, as far as the normalized components are concerned, because it exceeds the minimum instrumental level of 10 uA/m. Conversely, the 23.4 kHz failure, either due to an interruption of the transmitter or to propagation phenomena, prevents prospecting from continuing. More generally, the temporal variations can be investigated with reference to all frequencies received in a given area; this is performed by recording the signal spectrum in the 15-30 kHz band, at regular time intervals. This method furnishes supplementary information, such as interruptions of the transmitters, number and frequencies of the stations that can be used in the prospecting area, accidental variations in the transmission power, propagation characteristics related to the geographical position of the source, and so on.

Figure 8 illustrates an example of a spectrum recorded at Genova. Its systematic repetition over time makes it possible to evaluate the reliability of each single station at the measuring site. Such kind of control, performed si-

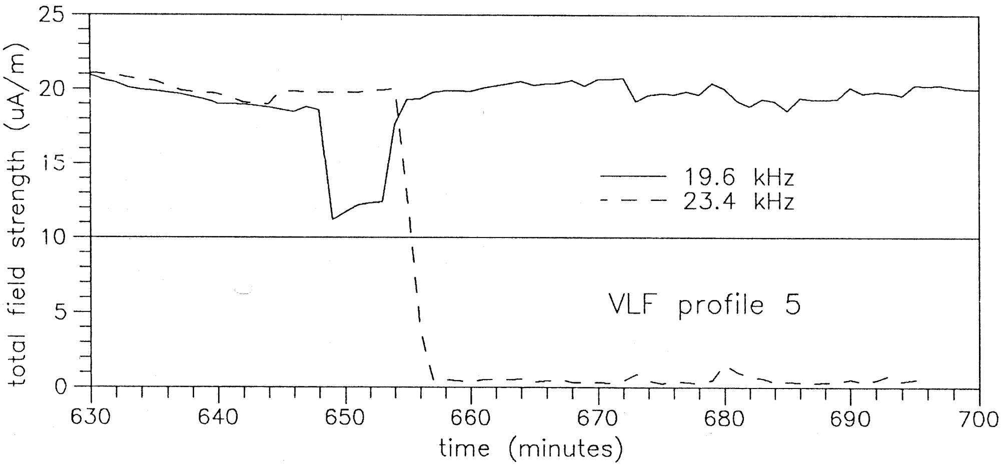

Fig. 7. An example of time variation of the total field at two different frequencies (from prospecting for a civil purpose, Genova, NW Italy).

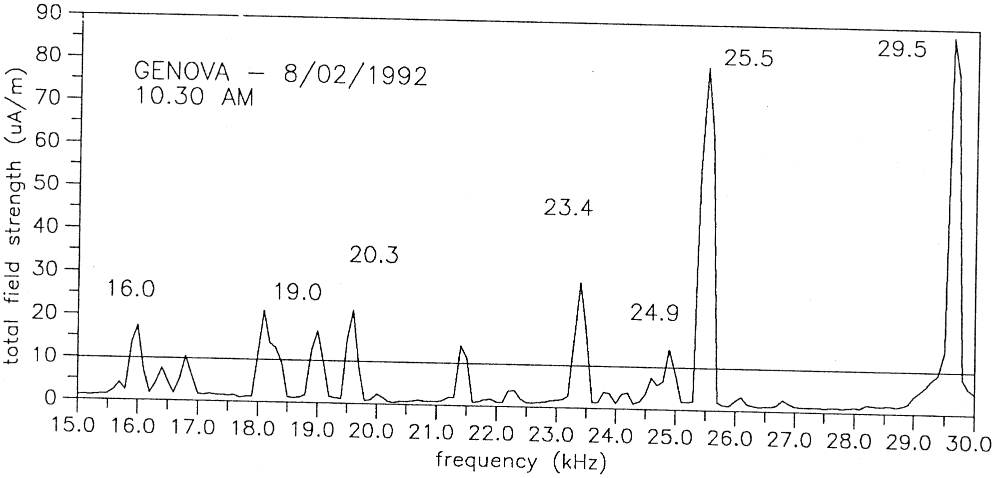

Fig. 8. The spectrum of the frequencies which can be utilized in the zone of Genova (NW Italy), as determined during instrument initialization.

multaneously with the recordings of fig. 7 and in the same place, showed that the different behaviour of the total field, which appears in this figure, is not due to an interruption of the transmitter at 23.4 kHz, but to a meteorological phenomenon, affecting the two stations differently (different frequencies, distances and source directions).

7. Anthropic noise

Some fluctuations of the VLF measurements, which are not caused by temporal or spatial variations of the signal, often occur; these fluctuations are ascribed to anthropic noise and they can also be investigated to find the buried path and geometry.

Some of these fluctuations produce noise with a typical morphology which helps to identify them. Figure 9 illustrates the morphology of the noise due to an aerial power line on a measurement profile. For the first thirty meters the signal becomes saturated and the noise still appears up to a distance of about 80 m. Though the frequency of the power line is very different from that of the VLF 19.6 kHz transmitter, mutual induction phenomena do occur.

The characteristics of a buried cable, without electric current, are different (fig. 10). The amplitude of the noise is smaller and is quite clearly of dipolar nature; therefore it behaves in a way that is typical of an inductive element, fed by the VLF electromagnetic signal. This noise source, though not directly observable, can be easily identified, since the perturbation has very regular development and symmetry. A similar behaviour is exhibited by pipelines and aqueducts; however the greater size and current flow, applied to prevent galvanic corrosion, generate stronger electromagnetic noise.

Some structures, such as telephone cables, metallic fences, railings and intense road traffic, can introduce noise in VLF prospecting. Fences, for instance, act like polarizing antennas and introduce steady components which amplify the secondary contributions and distort the base level of the resulting VLF field.

8. The role of surface conductivity

For the purpose of quantitative VLF interpretation, the model is restrictive, that an optimum, intense and non-distorted response is expected. The models of Vozoff (1971), Ward *et al.* (1974) and Kaikkonen (1979) are applicable to structural situations which are too simplified

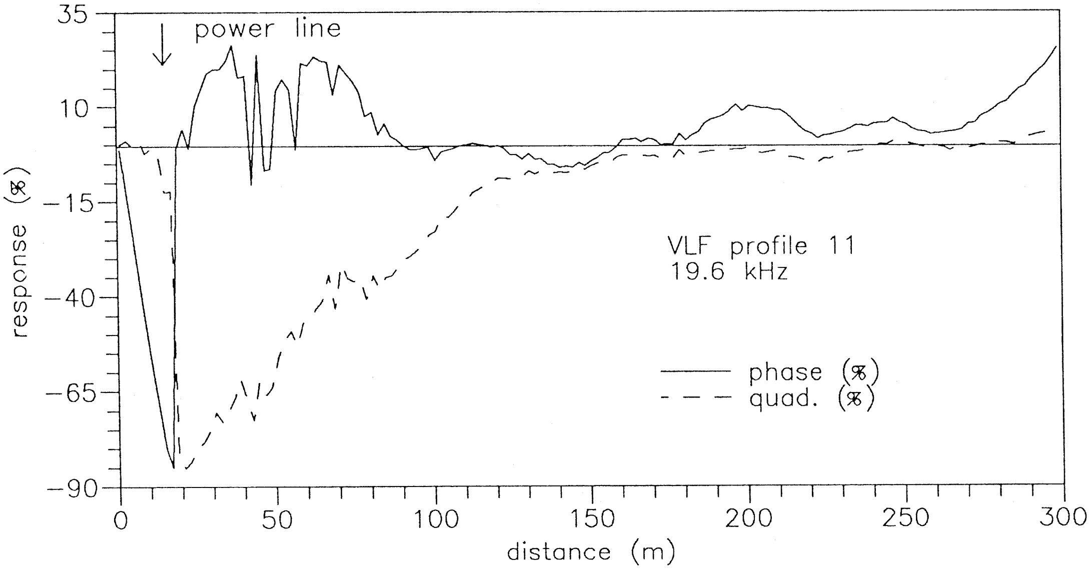

Fig. 9. A perturbation of anthropic origin, ascribed to an aerial high voltage electric line (from hydrogeological prospecting at Bonassola, La Spezia, NW Italy).

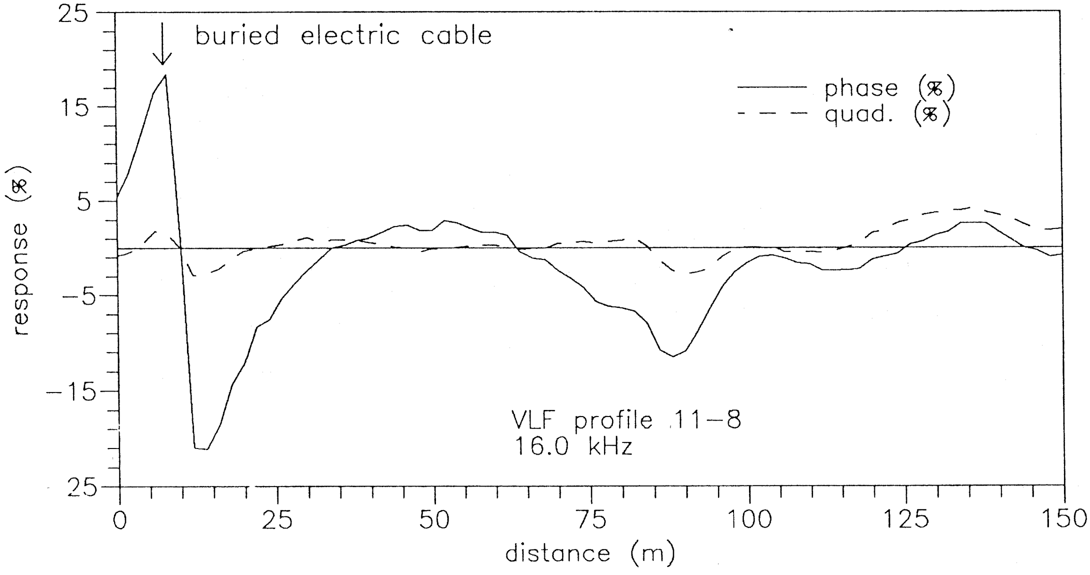

Fig. 10. A perturbation of anthropic origin, ascribed to a buried cable, without electric current (from archaeological prospecting at Poliochni, Lemnos island, Greece).

and do not include the effect of conductive overburdens. The high electrical conductivity of the latter prevents the transmission of the electromagnetic wave to depth; this causes a reduction of the investigated thickness and a marginal penetration of the subsoil. Olsson (1980) studied various models for which the electrical conductivity and the thickness of the overburden are changed and the other parameters remain constant: it turns out that the response is controlled by these two parameters. Subsequently, Sinha (1990a,b) proposed methods for evaluating the depth, thickness and dip of laminar conductors, without conductive overburdens. The presence of conductive overburdens is a major difficulty in VLF electromagnetic prospecting (Saydam, 1981).

If information on the resistivity of the medium, such as overburden, substratum and local stratigraphy, is available, VLF prospecting may offer complementary data. If the resistivity of the overburdens is low, experimental results emphasize the undulations of the resistive substratum, rather than the presence of conductors having a mainly vertical extension; *i.e.* the trend of the electromagnetic parameters shows the variations in the thickness of the conductive cover.

An example of application of VLF measurements under these circumstances is given in fig. 11, which shows a map of the in-phase component developed at the Poliochni site, (Lemnos Island, Northern Aegean Sea), from some profiles performed for archaeological purposes.

Geoelectrical prospecting previously determined the mean value of the resistivity of the cover (about 20 ohm*m) and the depth of the substratum (about 3-4 m), formed by a paleosoil with a resistivity of about 50 ohm*m. The undulations appearing in the map of the in-phase component are related to the maxima and minima of the thickness of the conductive cover, directly surveyed with drilling, which has confirmed this information. The map of the in-quadrature component (fig. 12), which is

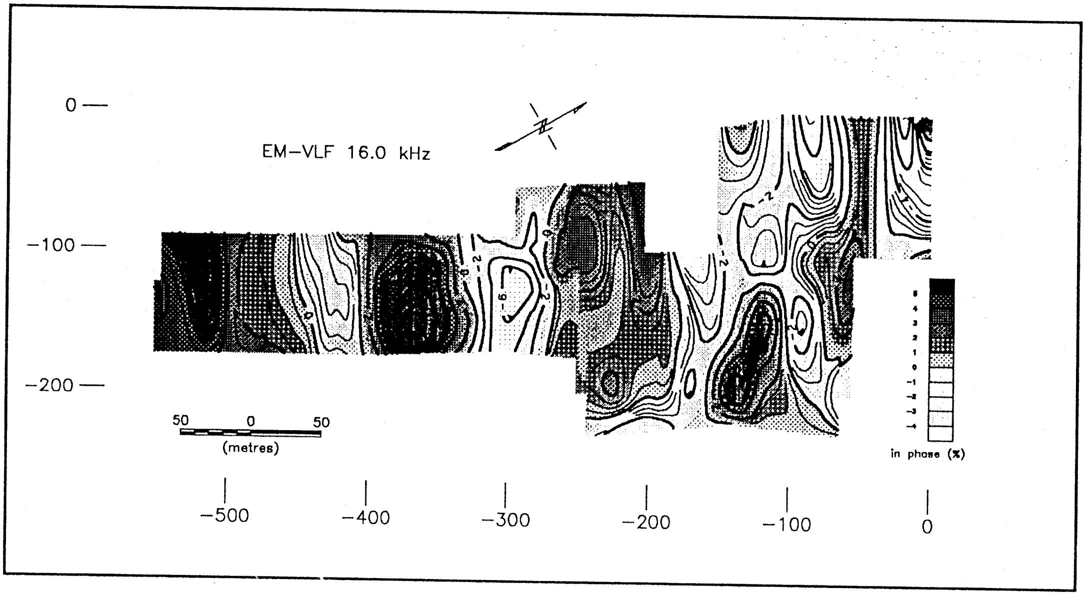

Fig. 11. The map of the in-phase component developed for stratigraphic purposes to emphasize the morphological changes of the cover and substratum (from archaeological prospecting at Poliochni, Lemnos island, Greece).

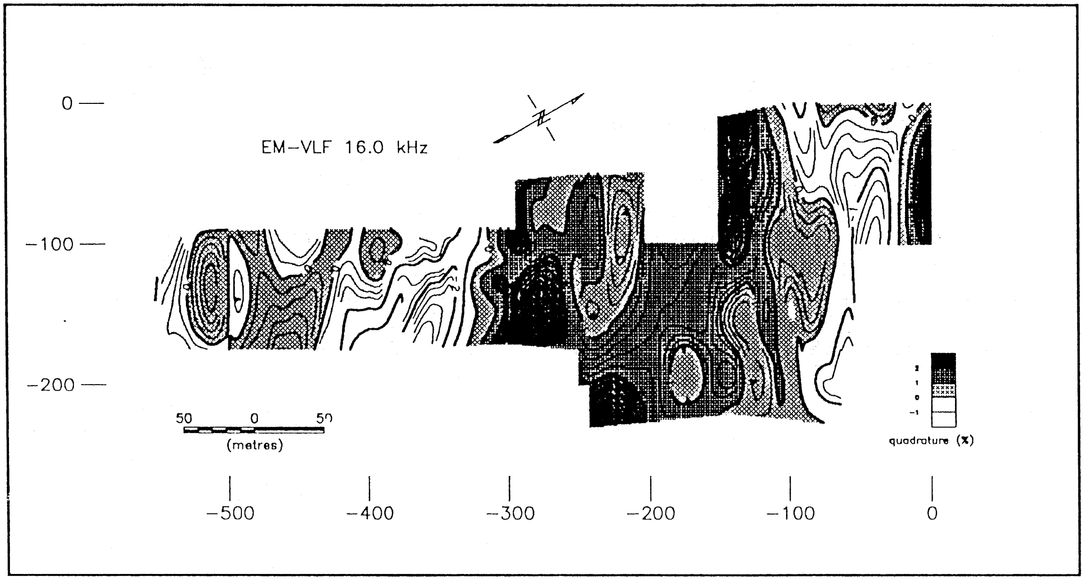

Fig. 12. The map of the in-quadrature component for the same area of fig. 11.

more directly controlled by induction phenomena in the overlying conductive medium (cover), supplies information on the homogeneity of the latter.

9. Conclusions

The systematic application of the VLF electromagnetic prospecting technique to various research fields, gave satisfactory operative and methodological results. This technique was therefore examined in terms of its intrinsic characteristics, rather than through the obtained results, that are presented in other works.

Besides the difficulty of fully analysing the utilized electromagnetic field and the scarcity of applications, apart from mining and structural geology topics, the most important conclusions may be summarized as follows:

– the use of multichannel receivers is suggested in order to take advantage of the changeability principle, pointed out for different frequencies with similar arrival azimuths, or of the simultaneous acquisition of signal with different azimuths, that is useful when there are no previous indications about the orientation of the targets;

– the transition from the unidimensional investigations (profiles) of VLF parameters to two-dimensional (areal) ones requires a series of operative mechanisms, which do not depend only on the strike of the profile, but also on the angle between the azimuth of the profile compared to that of the transmitter. This parameter should be systematically controlled, to ascertain whether inversions in polarity are ascribed to the subsoil conductors or to the irregular method of performing measurements;

– the evaluation of the topographic effect on the measured values has shown that, if the slope of the measurement profile is uniform (monotone), its influence on the interpretation of the data is negligible;

– it was verified that the use of transmitters at a distance of more than 500 km strongly reduces the influence of the variations of the primary field. The effect of the temporal variations is automatically eliminated by utilizing parameters normalized to the primary field. For prospecting in the total field, a base station for monitoring during the survey is needed. The availability of the time recording of the signal amplitude, besides the necessary corrections, improves the quality control of the measured parameters;

– the analysis of the VLF signature, with reference to sources of anthropic noise, suggests a preliminary investigation on the area to locate sources of anomalies which should be eliminated when processing data;

– the VLF technique used in presence of conductive overburdens leads the morphology of the stratigraphic relations to be enhanced. This is the same as showing the variations in the thickness of the conductive cover.

REFERENCES

ABDUL-MALIK, M.M., J.O. MYERS and J. MCFARLANE (1985): Model studies of topographic noise in VLF-EM data: accounting for the direction of morphological strike relative to survey line and magnetic field directions, *Geoexploration*, **23**, 217-225.

BAKER, H.A. and J.O. MYERS (1980): A topographic correction for VLF-EM profiles based on model studies, *Geoexploration*, **18**, 135-144.

BOZZO, E., F. MERLANTI, G. RANIERI, L. SAMBUELLI and E. FINZI (1992): EM-VLF soundings on the eastern hill of the archaeological site of Selinunte, *Boll. Geofis. Teor. Appl.*, **34**, 134-135, 169-180.

CLOOS, E. (1934): Auto radio, an aid in geological mapping, *Amer. J. Sci.*, **28**, 160.

EBERLE, D. (1981): A method of reducing terrain relief effects from VLF-EM data, *Geoexploration*, **19**, 103-114.

EPPELBAUM, L. V. (1991): Examples of terrain corrections in the VLF method in the Caucasian region, USSR, *Geoexploration*, **28**, 65-75.

KAIKKONEN, P. (1979): Numerical VLF modelling, *Geophysical Prospecting*, **27**, 815-834.

OLSSON, O. (1980): VLF anomalies from a perfectly conducting half plane below an overburden, *Geophysical Prospecting*, **28**, 415-434.

SAYDAM, A.S. (1981): Very low frequency electromagnetic interpretation using tilt angle and ellipticity measurements, *Geophysics*, **46** (11), 1594-1605.

SHARMA, P. V. (1986): *Geophysical Methods in Geology* (Elsevier Pubb. Co., New York), pp. 304.

SINHA, A.K. (1990a): Interpretation of ground VLF EM data in terms of inclined sheet like conductor models, *PAGEOPH*, **132** (4), 733-756.

SINHA, A.K. (1990b): Interpretation of ground VLF EM data in terms of vertical conductor models, *Geoexploration*, **26**, 213-231.

VALLÉE, M.A., M. CHOUTEAU and G.J. PALACKY (1992a): Variations of the VLF-EM primary field: analysis of airborne survey data, New Brunswick, Canada, *Geophysics*, **57** (1), 181-186.

VALLÉE, M.A., M. CHOUTEAU and G.J. PALACKY (1992b): Effect of temporal and spatial variations of the primary signal on VLF total-field surveys, *Geophysics*, **57** (1), 97-105.

VOZOFF, K (1971): The effects of overburden on vertical component anomalies in AFMAG and VLF exploration: a computer model study, *Geophysics*, **36**, 53-57.

WARD, S.H., J. RYU, W.E. GLENN, G.W. HOHMANN, A. DEY and B.D. SMITH (1974): Electromagnetic methods in conductive terranes, *Geoexploration*, **12**, 121-183.