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A new method of geoelectrical prospecting by vertical electric current soundings

V. Mogilatov *, B. Balashov

Siberian Research Institute of Geology, Geophysics and Mineral Resources, Novosibirsk, Russia

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Abstract

Some advantages and problems of a new geoelectrical prospecting method, vertical electric current soundings (VECS) are discussed. This method is based on using a new source, circular electric dipole (CED). The source is installed in the following way. One of the transmitter poles is grounded in the central point. The other pole is uniformly grounded around with a radius determined by the depth of investigation desired. It can be defined as a noninductive source. The most interesting CED properties in the low frequency regime are as follows. CED has no magnetic field of its own. It is a pure galvanic source, which differs from a loop (a pure inductive source) and from a line, which is both galvanic and inductive (a 'line' here means a cable or insulated wire grounded at its end points). The normal magnetic field on the earth's surface (and above it) of a horizontally layered medium is absent (within the quasi-static approximation), and only a radial electric component exists. A CED field is at right angles to the loop field and has azimuthal symmetry. The CED field is always governed by a vertical medium structure (at the latter transient stage as well) rather than by the total longitudinal conductivity. An interesting result was obtained: in marine electrical prospecting a sea water layer will not play such a crucial role when a CED is used as in applying a loop or a line. In a medium with non-conducting basement the decay of the CED field is exponential. The transient process is more fast than in the case of a loop or a line. The CED can be also considered as a ground analogue of another known source, a vertical electric line. Besides, the CED is a pure galvanic source that does not excite a long-term transient field. Thus it seems to be a new useful means to study IP processes. The mathematical apparatus is represented in the frequency and time domain. The authors consider the results of the initial field tests.

Keywords: electrical prospecting; transient; circular electric dipole; vertical electric current soundings

1. Introduction

The proposed electrical prospecting method is principally based on using a qualitatively new controlled source, a circular electric dipole (CED) (Mogilatov, 1992).

* Corresponding author. E-mail: mogilatov@geophys.nsk.su

Efficiency of a method for electric prospecting depends on several components. The choice of electromagnetic field source may be the key factor. A correct choice of source creates an optimal space–time structure for the electromagnetic field that best interacts with target objects, providing real physical preconditions for solving the problem at hand.

We propose the new source as an alternative to the classical sources, a loop and a horizontal electri-

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cal line. It seems most reasonable to classify it as a source with no magnetic field of its own. It means that we put forward such a geometry of the array on the earth's surface that allows us to considerably attenuate a magnetic field of each conductors making up the transmitter as a whole. In other words, CED is a noninductive source.

How should this source be arranged? Assume that we have at our disposal a limitless amount of wire segments, AB lines. Each of them is a source both inductive and galvanic. Connecting and grounding the segments in various ways we can form infinitely many different sources inductive and galvanic to a variable degree. Two classes can be distinguished among them. One is closed ungrounded circuits (loops), the sources purely inductive and well known in the electrical prospecting. The other class, distinctly recognized, will appear if we can do away with inductive component typical of an individual line. The only way to do this is to distribute lines with equal currents uniformly in radial directions. In such a manner we obtain a circular electric dipole — a pure galvanic source devoid of its own magnetic field. Fig. 1 illustrates reasoning cited above.

A CED can be described as a focusing source with more reason than any other source setup. Indeed, the maximum density of the vertical current created by a central electrode remains under the electrode throughout the transient process and merely goes deeper into the medium.

The CED field is always determined by the vertical structure of the medium, and at the late stage of the transient as well, not by total longitudinal conduction. One interesting outcome can be mentioned.

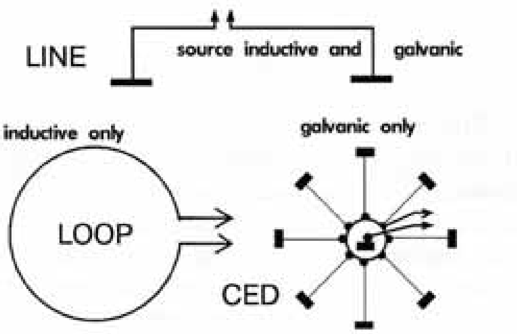

Fig. 1. Three types of sources in electrical prospecting by the transient field.

In the marine electrical prospecting a sea water layer will not play such a fatal role in using the CED as in using the loop or line. In the medium with non-conducting basement the CED field decays exponentially. Generally, the transient process is 5–10 times faster than that from the loop or from the line.

One can also consider the CED as an analog of the other known source, namely the vertical electric dipole (VED).

Any closed circuit (loop) and CED can also be described mathematically as an assemblage of electric dipoles. Still, it is more convenient to introduce physical objects — a vertical magnetic dipole representing a loop field and a circular electric dipole for a pure galvanic source.

The label 'CED' (circular electric dipole) can seem to be unsuccessful sometimes. However, it is difficult to find a replacement. This label is a work name, which is conformable to VED, HED and VMD.

Taking into consideration a pronounced vertical character of the currents under the central electrode and current circulation in the vertical planes we propose to term the electrical prospecting technique using the CED the vertical electric current sounding method (VECS). Some possibilities of the application VECS are considered in this work on using theoretical and field test materials.

2. Theoretical

In this section we give mathematical apparatus for the CED field in the compact form. It is necessary for this quite new source.

2.1. Model and vector potential

As indicated in Fig. 2 the model is radial current sheet $j_r(r)$ in A/m locates in the interface between homogeneous and layered half-spaces. The upper region, for $z > 0$, which we refer to as the air, has permittivity ϵ_0 and permeability μ_0. The lower lossy region, which we refer as the earth, has permittivity ϵ_i, conductivity σ_i and permeability μ_0 in the i-th layer ($i = 0, 1, 2, \ldots, N-1, N$. H_i ($i = 1, 2, \ldots, N$, $H_1 = 0$) are depths of the boundary. The origin of coordinates is on the ground surface, the axis is

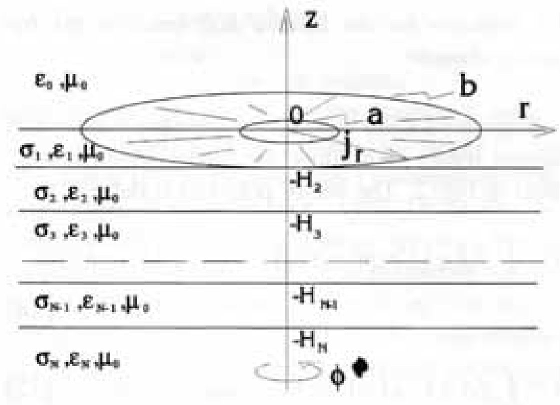

Fig. 2. The model.

directed upwards. The objective is to deduce expressions for the fields everywhere terms of the specified source current $j_r(r)$.

So, a time factor $\exp(j\omega t)$ is assumed where ω is the angular frequency. Because of azimuthal symmetry, the fields can be derived from the vector potential which has only a z component. Thus, the non-zero field components are:

$$E_r = \frac{1}{\sigma + j\omega\epsilon} \cdot \frac{\partial^2 A}{\partial r\,\partial z},$$

$$E_z = \frac{1}{\sigma + j\omega\epsilon} \cdot \left(-\gamma^2 + \frac{\partial^2}{\partial z^2} \right) A, \qquad H_\phi = -\frac{\partial A}{\partial r}, \tag{1}$$

where $\gamma^2 = j\omega\sigma\mu_0 + (j\omega)\epsilon^2\mu_0$. In the air $\sigma_0 = 0$.

2.2. *Excitation of a half-space by a radial current sheet* [1]

Now we assume that the lower region (i.e., the earth) is homogenous half-spaces and has permittivity ϵ_1, conductivity σ_1 and permeability μ_0. The non-zero field components are as in (1).

The first boundary condition is very simple. It states that E_r is continuous through the plane $z = 0$, thus:

$$E_r(z = +0) - E_r(z = -0) = 0. \tag{2}$$

[1] In this subsection we used a private communication from James R. Wait, reproduced with his permission.

The second boundary condition, following from Faraday's law, is that:

$$H_\phi(z = +0) - H_\phi(z = -0) = -j_r(r). \tag{3}$$

To implement these conditions, we employ the following integral representations:

$$A = \int_0^\infty f_0(g) \cdot \exp(-u_0 z) \cdot J_0(gr)\,\mathrm{d}g, \quad z \geq 0, \tag{4}$$

$$A = \int_0^\infty f_1(g) \cdot \exp(+u_1 z) \cdot J_0(gr) \cdot \mathrm{d}g, \quad z \leq 0. \tag{5}$$

where $u_0 = (g^2 + \gamma_0^2)^{1/2}$ and $u_1 = (g^2 + \gamma_1^2)^{1/2}$. Notice that $J_0(gr)$ is the Bessel function of order zero, it is verified that A satisfy Helmholtz equation $(\nabla^2 - \gamma^2)A = 0$.

The remaining task is to determine $f_0(g)$ and $f_1(g)$. On using (1)–(5) we obtain:

$$f_0(g) = \frac{-j\omega\epsilon_0 u_1 S(g)}{(\sigma_1 + j\omega\epsilon_1)u_0 + j\omega\epsilon_0 u_1},$$

$$f_1(g) = \frac{(\sigma_1 + j\omega\epsilon_1)u_0 S(g)}{(\sigma_1 + j\omega\epsilon_1)u_0 + j\omega\epsilon_0 u_1}, \tag{6}$$

were:

$$S(g) = \int_0^\infty j_r(r) \cdot r \cdot J_1(gr)\,\mathrm{d}r. \tag{7}$$

On inserting these expressions into (4) and (5) we have a formally, exact solution valid for any specified radial current density $j_r(r)$. Corresponding exact expressions for the field components are obtained by performing the derivative operations indicated by (1).

We now specialize the radial density to be:

$$\begin{aligned} j_r(r) &= I_0/(2\pi r), && \text{for } a \leq r \leq b, \\ j_r(r) &= 0, && \text{for } r < a \text{ and } r > b, \end{aligned} \tag{8}$$

where I_0 is the total current flowing across the annular strip. In this case:

$$S(g) = \frac{I_0}{2\pi} \cdot \int_a^b J_1(gr)\,\mathrm{d}r = \frac{I_0}{2\pi g} \cdot [J_0(ga) - J_0(gb)]. \tag{9}$$

This form for $S(g)$ would be appropriate for a pair of circular grounded electrodes of radii a and b. To preserve the assumed symmetry, they are being excited by a large number of insulated wires carrying a total current I_0. Of course, if $a \to 0$ we have a point electrode at the center whence $J_0(ga) = 1$. If we further allow $gb \ll 1$, $J_0(gb) \approx 1 - g^2b^2/4$ and then:

$$S(g) \approx \frac{I_0 b^2}{8\pi} g. \tag{10}$$

This appears to be a valid approximation, $b \ll r$ (i.e. the radial coordinate of the observe is much greatly than outer ring electrode). To simplify the subsequent discussion, we assume this is the case in what follows.

For most geophysical applications another simplification can be made. That is, if $|\gamma_0 r| \ll 1$ (i.e. r much less than the wave-length in air), $u_0 \simeq g$ so that the fields in the upper air region are valid solutions to Laplace's equation. This is what is meant by the 'quasi-static' assumption. But bear in mind that displacement currents are not ignored. However we will say that the lower earth half-space is assumed to be well conducting in the sense that $|\sigma_1 + j\omega\epsilon_1| \gg \epsilon_0\omega$. Under these conditions (4) and (5) simplify to:

$$A \simeq -\frac{I_0 b^2}{8\pi} \frac{j\omega\epsilon_0}{\sigma_1 + j\omega\epsilon_1} \int_0^\infty u_1 \exp(-gz) \cdot J_0(gr)\,\mathrm{d}g, \quad z \geq 0, \tag{11}$$

$$A \simeq \frac{I_0 b^2}{8\pi} \int_0^\infty g \cdot \exp(u_1 z) \cdot J_0(gr)\,\mathrm{d}g, \quad z \leq 0. \tag{12}$$

To deal with the case $z < 0$ (i.e. within earth), we obtain rather simply from (12) that:

$$A = \frac{I_0 b^2}{8\pi} \frac{\partial}{\partial z} \int_0^\infty \frac{g}{u_1} \exp(u_1 z) \cdot J_0(gr)\,\mathrm{d}g = -\frac{I_0 b^2}{8\pi} \frac{z}{R^3} (1 + \gamma_1 R) \exp(-\gamma_1 R), \tag{13}$$

where $R = \sqrt{r^2 + z^2}$.

2.3. Solution for the layered half-space in the frequency domain

Consider a CED field in the arbitrary horizontally layered media. We adopt the model which is indicated in Fig. 2. The vector potential is defined as:

$$A = \int_0^\infty f_0(g) \cdot \exp(-u_0 z) \cdot J_0(gr)\,\mathrm{d}g, \quad z \geq 0, \tag{14}$$

$$A = \int_0^\infty f_1(g) \cdot \zeta(z) \cdot J_0(gr)\,\mathrm{d}g, \quad z \leq 0, \tag{15}$$

The function $\zeta(z)$ is defined successively from the bottom upwards:

in the lower half-space ($z < -H_N$):

$$\zeta(z) = \exp[u_N(z + H_N)], \tag{16}$$

in the i-th layer ($\zeta_i = \zeta(-H_i)$, $\zeta_i' = \zeta_z'(-H_i)$):

$$\zeta(z) = \zeta_{i+1} \cdot \cosh[u_i(z + H_{i+1})] + \frac{\zeta_{i+1}'}{u_i} \cdot \sinh[u_i(z + H_{i+1})], \tag{17}$$

ζ and $\zeta'/(\sigma + j\omega\epsilon)$ being continuous through the plane $z = -H_i$. Here $u_i = \sqrt{g^2 + \gamma_i^2}$, $\gamma_i^2 = j\omega\sigma_i + (j\omega)^2\epsilon_i\mu_0$.

To implement the boundary conditions on the first boundary (2) and (3), we employ the following expressions for f_0 and f_1:

$$f_0(g) = -\frac{S(g) \cdot j\omega\epsilon_0 \cdot \zeta_1'}{(\sigma_1 + j\omega\epsilon_1) u_0 \zeta_1 + j\omega\epsilon_0 \zeta_1'},$$

$$f_1(g) = \frac{S(g) \cdot (\sigma_1 + j\omega\epsilon_1) \cdot u_0}{(\sigma_1 + j\omega\epsilon_1) u_0 \zeta_1 + j\omega\epsilon_0 \zeta_1'}. \tag{18}$$

In the quasi-static approximation, $u_i = \sqrt{g^2 + j\omega\sigma_i\mu_0}$ and

$$f_0(g) \simeq 0, \qquad f_1(g) \simeq \frac{S(g)}{\zeta_1}. \tag{19}$$

It is a remarkable result. In the quasi-static approach there is no magnetic response of layered earth in the upper region (air).

2.4. The time domain solution

The formal time domain solution is the Fourier transform of the equation in the frequency domain. We propose here another solution known as a method of transient spatial harmonicities (Tikhonov and Skugarevskaya, 1950; Mogilatov, 1992, 1993). This solution is valid in the quasi-static approach for the geoelectrical sections with non-conducting or perfectly conducting basement. So, if $\sigma_0 = 0$, $\sigma_N = 0$ and $\epsilon_i = 0$ $(i = 0, 1, \ldots, N)$, for the step function excitation (turning-off), the time domain solution can be represented as follows:

$$e_r(r, z, t) = \frac{1}{\sigma}\frac{\partial^2 A}{\partial r \partial z},$$

$$e_z(r, z, t) = \frac{1}{\sigma}\frac{\partial^2 A}{\partial z^2} - \mu_0 \frac{\partial A}{\partial t},$$

$$h_\phi(r, z, t) = -\frac{\partial A}{\partial r} \tag{20}$$

where

$$A = \int_0^\infty J_0(gr)\left[\sum_{l=1}^{\infty} f_l(g)\,\zeta_l(z)\cdot\exp(-\eta_l t)\right]\mathrm{d}g,$$

$$0 \geq z \geq -H_N, \tag{21}$$

$A = 0$, if $z > 0$ or $z < -H_n$. Here

$$f_l = \frac{S(g)\cdot\zeta'_{l1}}{\sigma_1 \mu_0 \eta_l \Sigma_{i=1}^{N-1} M_{li}},$$

and

$$M_{li} = \int_{H_i}^{H_{i+1}} [\zeta_l(z)]^2\,\mathrm{d}z$$

$$= \frac{1}{2u_{li}^2}\big[(H_{i+1} - H_i)(\zeta_{li}^2 \cdot u_{li}^2 - [\zeta'_{li}]^2)$$

$$+ (\zeta_{li+1}\zeta'_{li+1} - \zeta_{li}\zeta'_{li})\big].$$

The function $\zeta_l(z)$ is defined successively from the top down: $\zeta_l(0) \equiv \zeta_{l1} = 0$, $\zeta'_{l1} = g$, in the i-th layer

$$\zeta_l(z) = \zeta_{li}\cdot\cosh[u_{li}(z + H_i)]$$

$$+ \frac{\zeta'_{li}}{u_{li}}\cdot\sinh[u_{li}(z + H_i)], \tag{22}$$

ζ_l and ζ'_l/σ being continuous through the plane $z = -H_i$. Here $u_i = u_i = \sqrt{g^2 - \sigma_i \eta_l \mu_0}$. The condition on the lower boundary $\zeta_l(-H_N) \equiv \zeta_{lN} = 0$ is the equation for η_l.

All the algorithms described here are realized in the form of programs for direct current, in frequency domain and in time domain (in two ways). The programs are used as a compound of dialogue packages in IBM PC.

2.5. Electric component of the CED field

So, a radial electric component is the only component on the ground surface indicative of the process of current transition to a steady state in a horizontally-layered medium (in the quasi-static approximation). We understand that the above mathematical apparatus is inadequate in actual conditions because of failure to take account of IP effects. However, to analyze characteristics of the new source in nonpolarizing media is the absolutely necessary stage and will be of practical significance in interpreting the results obtained in a real polarizing medium.

Now let us consider the CED field in two layer (σ-conductivity, d-thickness) medium (with non-conducting basement). On using general formulae (20), (21) and (22) we obtain on the ground surface:

$$e_r(t) = \frac{2}{\sigma d}\cdot\int_0^\infty J_1(gr)\cdot g\cdot S(g)$$

$$\cdot\left\{\sum_{l=1}^{\infty}\frac{u_l^2}{g^2 - u_l^2}\exp\left[-(g^2 - u_l^2)\frac{t}{\sigma\mu_0}\right]\right\}\cdot\mathrm{d}g, \tag{23}$$

where in this case we have an equation for u_l in the form $\sinh(u_l d)/u_l = 0$, i.e., $u_l = j\pi l/d$, $(l = 1, 2, \ldots)$.

It is clear that in the late stage (with $t \to \infty$) it is enough to take $l = 1$ and integral (23) is determined at small values of g. So, in late stage on using (10) for $S(g)$ we obtain:

$$e_r(t) \approx \frac{I_0}{4\pi\sigma d^2}\cdot\left(\frac{b}{d}\right)^2\cdot\frac{r}{d}\cdot\left(\frac{\sigma\mu_0 d^2}{2t}\right)^2$$

$$\cdot\exp\left(-\frac{\sigma\mu_0 r^2}{4t}\right)\cdot\exp\left(-\frac{\pi^2 t}{\sigma\mu_0 d^2}\right). \tag{24}$$

Thus, we demonstrate two properties of the CED field in the medium having insulating basis: exponential field decay in the late stage and its dependency on the vertical dimension of the medium as opposed to the fields of a loop and line, which are determined in the late stage only by the composite longitudinal conductance.

2.6. CED and VED

The CED can be considered as a ground analogue of another known source, namely, a vertical electric dipole (VED). The final expression (13) for the vector potential of CED in the half-space (within earth) is the same as if the source were replaced by a vertical electric dipole of current moment $(Idz)_e$ located at $z=-h$. On using the conditions $h \ll r$, $|\gamma_0 r| \ll 1$ and $|\hat{\sigma}_1| \gg \epsilon_0 \omega$ (i.e. as for CED) we have for VED (Wait, 1982):

$$A = \frac{(Idz)_e h}{2\pi} \cdot \frac{z}{R^3} \cdot (1+\gamma_1 R) \cdot \exp(-\gamma_1 R), \tag{25}$$

where $z > h$. On Eqs. (13) and (25) we see that the equivalent electric dipole moment relates to the disc current I_0 by

$$(Idz)_e h = I_0 b^2/4. \tag{26}$$

Now we shall compare the fields of CED and VED in time domain. An expression to asymptotic behavior $(t \to \infty)$ of the radial gradient of the VED field in a two-layered medium is (Goldman, 1990)

$$e_r(t) = \frac{(Idz)_e}{\pi^2 \sigma d^3} \cdot \sin\left(\frac{\pi h}{d}\right) \cdot \frac{r}{d} \cdot \left(\frac{\sigma\mu_0 d^2}{2t}\right)^2 \cdot \exp\left(-\frac{\sigma\mu_0 r^2}{4t}\right) \cdot \exp\left(-\frac{\pi^2 t}{\sigma\mu_0 d^2}\right). \tag{27}$$

where h is the depth of the VED. If $h \to 0$, we obtain that the field of VED (27) is equal to the field of CED (24) under the condition:

$$(Idz)_e h = I_0 b^2/4. \tag{28}$$

3. Direct observation of local object fields in VECS

As a rule an anomalous contribution of local objects or disturbances in the horizontal homogeneity of the section in transient field sounding methods is recorded against an intense background of host rock mass response. On the one hand, that poses problems in recording the response and on the other hampers the interpretation which consists in separating an anomalous part of the response at the first stage. The problem of suppression of the normal background of the host medium can be solved, among other factors, by optimizing the field source. One can consider the circular electric dipole as the optimized source with the lack of the normal magnetic field in mind.

It is evident that the effect of disturbance of the horizontal homogeneity of the section when using the CED-array can be illustrated solely by the three-dimensional mathematical or physical modeling. Not pretending strictness, showing the results of approximate calculations carried out by the disturbance method, we examine a host horizontally layered model of the medium and replace the heterogeneity with volumetric distribution of transient extrinsic currents determined by the normal electric field only. This approach gives a rather flexible computational procedure also suitable for some estimations under field conditions.

So, Fig. 3 shows the diagram of physical modeler and the results of mathematical and physical modeling. The model of the geoelectrical medium is a 'pit' in the lead layer (thickness is 6 cm). It is obvious that we have stated a problem to determine the location and dimensions of a non-conductor body with respect to the field observed on the surface. When the source (the 8-ray CED, radius 5 cm, total current in the pulse 17 A) was fixed, the magnetic induction (i.e. $\mu_0 \cdot dH_z/dt$) in the area was measured by the inductive coil (effective square 0.28 m * m). On the isoline map of the e.m.f. (mathematical modeling) the heterogeneity has manifested itself evident with some degree of definiteness. At the extrema which indicate the position of elongated body ends the e.m.f. values reach ± 6 μV. The transient curves have their maximum close to 3.5 ms. The isoline map is just given at this time. Fig. 3 shows also the physical modeling in comparison with the mathematical modeling along a profile at 3.5 ms. Here we have offered the results of measurements of the vertical component of the magnetic induction, and yet the heterogeneity is also well recorded in the horizontal components.

Note that having done away with the normal field by means of the optimized source, we at once alleviated technical problems of response recording. When the CED is used, the magnetic response of the medium completely caused by the heterogeneity is of narrow dynamic range, requirements on accuracy of

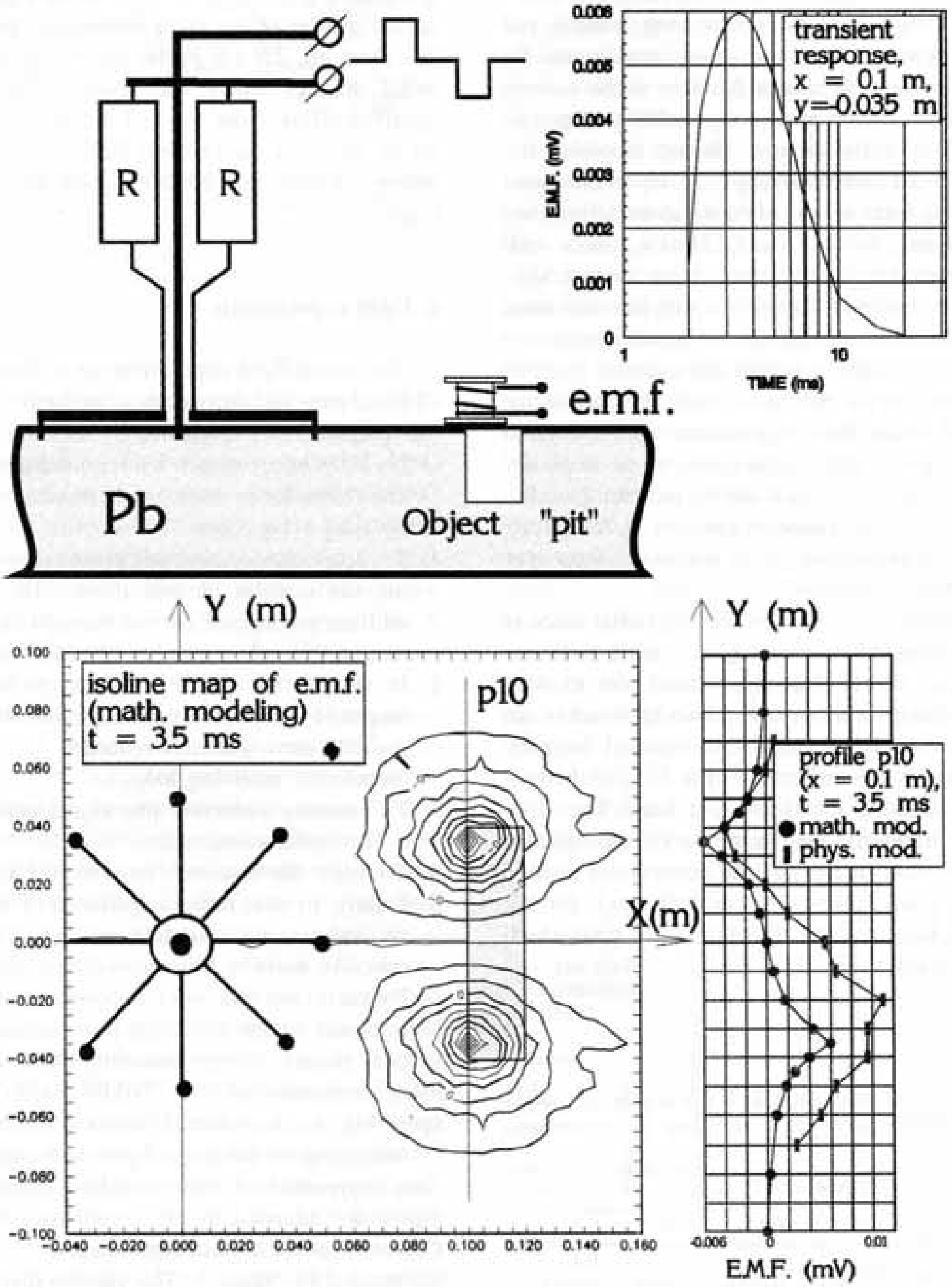

Fig. 3. The area measurement of the magnetic induction in VECS. The results of the mathematical and physical modeling.

its recording are not strong. This allows contracting the transmission band of the measuring system (pickup-meter) and significantly increasing its sensitivity.

However, an experienced reader understands that having solved some problems of recording and interpretation in the electrical prospecting method put forward here we did it under certain conditions. To comply with them is also a problem to be solved. First and foremost this is sure a possibility of practical realization of the circular electric dipole as the array without its own magnetic field. Up to this point our reasoning (and also mathematical modeling) has been based on a view of the CED as a source with ideal axisymmetric distribution of the current supplied into the medium. Actually we replace this ideal with the finite set of radially (at equal angles) arranged lines uniform in length and current. Preliminary calculations of the field from this conductor system and initial field experiments with the CED array have shown that requirements to the accuracy of length, angle and current can be judiciously satisfied. In the field experiments currents at rather different ground resistivities were equalized by a specially designed equipment.

The situation with the number of radial lines is more complicated. The residual magnetic field decreases more slowly than one would like to with increase in the number of lines. Two approaches are possible here. One is to render the residual 'normal' field negligible as compared to the field of heterogeneities increasing the number of lines. The other provides a trade-off, i.e. recording of the residual field of the array in interpreting observation results.

Table 1 gives values of a residual e.m.f. for the same array, host medium and at the same time which have been used above (Fig. 3). These data are obtained by means of the special procedure of calculating a transient field from an arbitrary set of electric lines in a horizontally layered medium. Such a procedure should necessarily become an element of the software for VECS. The e.m.f. values are indicated along such a radial profile where they are maximal (at the quarter of an angle between raypaths). Note, that there are $2N$ (N is the number of raypaths) of radial profiles where the residual magnetic field equals 0. Thus, from Table 1 it follows that with a set of six lines the residual field is to be recorded bearing in mind that a useful signal does not exceed 6 μV.

Table 1
The residual normal magnetic field (i.e. e.m.f. in μV in the receiver coil) at 3.5 ms for the medium and the configuration shown in Fig. 3

The number of rays	Distance (m)			
	0.08	0.1	0.12	0.14
6	0.64	0.82	0.7	0.4
8	0.002	0.0036	0.0039	0.0028

4. Field experiments

The initial field experiment on realization of the CED scheme and its operation in the transient mode was prepared and conducted by us from January 11 to 28, 1993 under severe winter conditions.

The following problems were planned to be solved in the field experiment:

1. To demonstrate technical potentialities of realizing the circular electric dipole, i.e. to provide uniform passage of current through the ground at various ground resistances of radial raypaths.
2. In solving the above problem, to show that a magnetic component on the ground surface tends towards zero which is recorded by e.m.f. value drop in the receiving loop.
3. To measure a receiver line signal when the CED is successfully realized.
4. To refine the necessary number of CED raypaths.
5. Finally, to gain initial experience of work by the vertical-currents sounding method (VCS) and to conceive ways of this method development.

To carry out the field experiment a simplified scale model of the electrical prospecting system of vertical electric current sounding (VECS) based on using equipment of the 'Tsikl-4' type was developed. Fig. 4 schematically shows a VECS set.

According to the control program currents in the lines (raypaths) of the controlled circular electric dipole are adjusted in the range from 0.1 to 5 A. Control over the current adjustment in the raypaths is maintained by block 5. The current diagram in the CED raypaths is set by GTE-45 current generator of

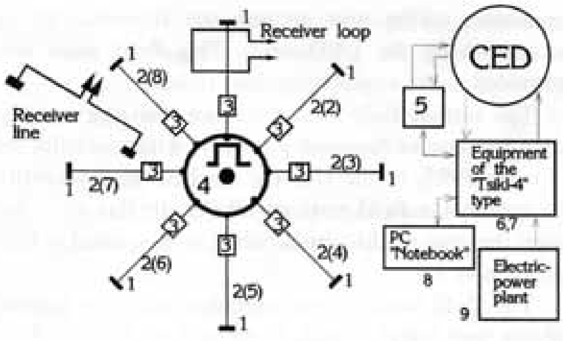

Fig. 4. The VECS set. 1 = outer electrode, 2 = line (raypath), 3 = control block of raypath current, 4 = central electrode, 5 = current measurement and adjustment block, 6 = GTE-45 current generator for the 'Tsikl-4' equipment, 7 = meter for the 'Tsikl-4' equipment, 8 = PC, 9 = electric-power plant.

the 'Tsikl-4' equipment. An electric-power plant carries the load (CED). Electromagnetic field parameters are measured by TsEI-4 meter of the 'Tsikl-4' equipment. A personal computer of the 'Notebook' type performs entry of auxiliary information, for example, date, set configuration, the number of measurement cycles, etc. Data recording through the RS-232 interface is executed on a PC floppy disk. A sounding array, a receiver loop and a MN line were located according to the chart given in Fig. 4.

The work was carried out with an 8-ray array. The raypath is 500 m long. Eight raypaths were assumed to be enough for practical realization of uniform grounding, but we intended to decrease that number from the experiment results. Theodolite was used to set angles between the raypaths. Each of the line ends was grounded by iron stakes 1 m long taken three at a time spaced at 2–3 m apart. Thus, the central grounding was formed by 24 driven stakes connected together. Resistivity of the grounded lines appeared to be rather different – from 5 to 70 Ω, perhaps due to unevenly frozen (ap to 0.4 m) upper layer of soil. We did not adjust the resistivities using the stakes having decided to examine operation of the current control system under such conditions.

An electric-field component was measured employing a 500 m long MN line. The MN line was located radially and symmetrically relative to the 7th and 8th raypaths of the array. A conductor from the array center to the first electrode of the line was 200 m long. Standard nonpolarizable electrodes were placed in earth below the freezing boundary (0.5 m).

The 100 * 100 m receiver loop was located (Fig. 4) at a distance (the loop center) of 250 m from center of whole array.

The first stage of the experiment consisted in testing the raypath current control system under field conditions. It is found that the system allows feeding any current from 0 to 5 A to each of the raypaths and ensuring stability of the given current distribution. In particular, in spite of the wide array in the line-end ground resistances, equal currents have been supplied to the lines which means the first realization of the circular electric dipole (CED) as a new source.

Of special note is the fact that the work has been conducted in the transient mode with the source operating under pulsed conditions. Loop and line receiver signals were recorded with accumulation.

Medium response in the receiver loop was recorded at various current distributions in the lines. We have ensured ourselves that surface magnetic field compensation occurs at equal currents.

At the second stage when there appeared the assurance of the real realization of the CED receiver signals were measured. Needless to say we have expected that the CED-MN array as a purely electric one will give a response greatly affected by IP process. However, we have believed that a part of the curve will be mainly determined by the inductive transient process which we calculated for the known medium (Fig. 5, curve 'transient'). We have actuality obtained the response (Fig. 5, the curve '8 raypaths') radically different of the transient signal and

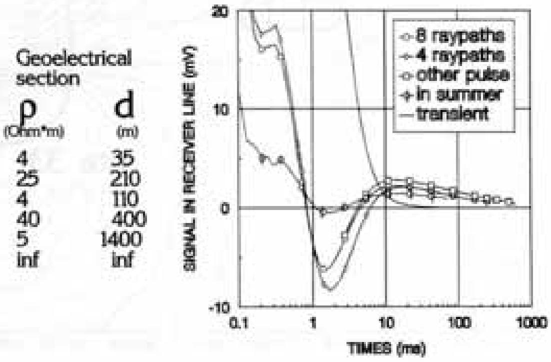

Fig. 5. The electrical response in VECS. The field test.

having two zero crossovers. At the end of the process the signal we have recorded exceeds the transient signal 500 times. When a 4-ray array is used, the signal practically does not change (the curve '4 raypaths').

So, most likely we have detected the complicated process in which the IP process plays the most important role that is basic in its second half because of short-duration of the transient process. This signal interpretation is possible if the mathematical software is developed, taking into account the IP processes.

In view of the unusual character of the receiver line signal the results of the first field experiments needed further check, especially as a new transmitting array was used. In summer, i.e. under absolutely different season conditions, the electric component was remeasured at the same site. The measurements qualitatively confirmed the winter results (Fig. 5, the curve 'in summer').

We also performed various tests in which current pulse and pause duration varied (Fig. 5, the curve 'other pulse'). So, we obtained experimental data necessary to develop and correct the mathematical apparatus taking into account the IP processes in excitation by the CED-array. This field work has provided some engineering experience.

The further field tests were not realizing in long time because of financial problems. Only recently, in autumn 1995, in the Ukraine we had the possibility to continue a field tests of VECS. In this case we used the area modification, which is described before in Section 3.

The field works were executed with the known object (ore body), which is defined by TEM and by boring (much approximately) at a depth of 400 m. The transmitter (CED, 500 m) was disposed 1000 m from the object. The current in each raypath was 0.9 A only because of large resistance of the host medium (2000 Ω m). The measurements were realized by self-contained synchronized unit. This unit combined a meter of the equipment 'Tsikl-4' and compact inductive pickup (the effective square is 10000 m ∗ m).

Fig. 6 shows results of these field works. Fig. 6a shows the situation as a whole, the isoline map (mathematical modeling) of e.m.f. (at fixed time) and three profiles, which were used for the measure-

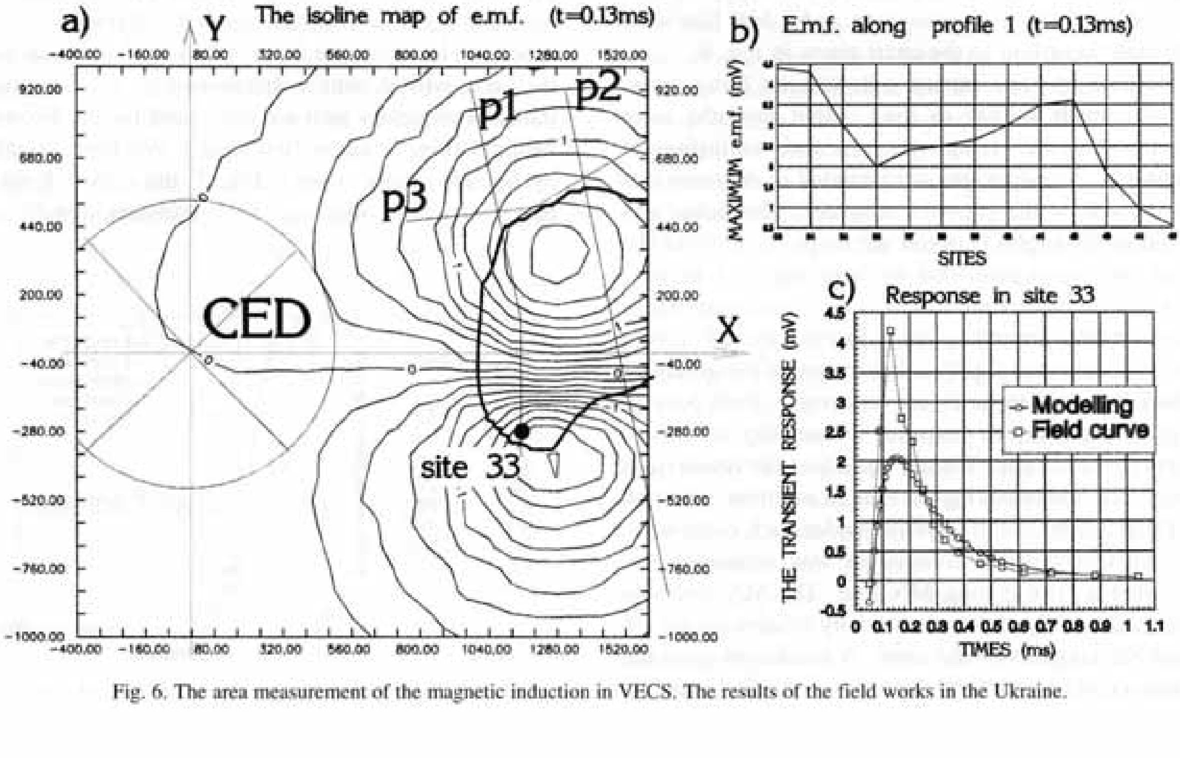

Fig. 6. The area measurement of the magnetic induction in VECS. The results of the field works in the Ukraine.

ments in fact. The results of the field measurements along profile 1 are shown in Fig. 6b. The edges of the ore body have made itself by the maximums of e.m.f. (sign of e.m.f. was not registered). Fig. 6c display typical transient responses (field and modeling) in site 33 of profile 1.

We believe that these field works were successful and we have obtained a geological result (the edges of the ore body are specified).

5. Conclusions

We are well aware of a usual response of a specialist in electrical prospecting to the transmitting array we put forward — too many wires, groundings and it is difficult to be installed. This is not entirely true. If we replace a AB line with the CED-array then at the same total current we will need the same amount of wire and grounding in terms of weight for the CED-array with a radius equal to the AB length. We should divide the conductive section of the AB line into N veins (and groundings, correspondingly) and locate them on radii. However, to reach the same depth of penetration as that in the case of the AB line a considerably shorter radius is required.

Thus, the CED device needs much less wire (by weight) than the AB line or the loop. It should be also noted that a thin light wire is used. To lay it out by hand without transport facilities two persons are enough, one of which controls its laying from the center using a theodolite.

The most important problem is to ensure equal currents in the array rays in the pulse mode. We convinced ourselves that this problem can be settled and implemented one of the variants in field situation.

A major disadvantage of the CED scheme as described above is the need to provide a symmetrical grounding of the outer ring electrode. A possible way to avoid this requirement is to adopt an unterminated model (this idea was proposed by J.R. Wait in a private communication). The CED scheme with ungrounded terminations can be efficient in the high frequency domain.

It has been our intent to demonstrate basic possibilities of the new source and to assure a reader in the feasibility of the new transmitting CED-array. On solving more practical problems already touched on (namely, the residual magnetic field, surface heterogeneities, correction for the IP processes) one may expect to receive a new effective instrument for geoelectrical investigations.

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