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A circular electric dipole: a transmitter for TEM surveys

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Abstract

Much experience has been gained lately in the use of a radial current source, the so-called circular electric dipole (CED), as a transmitter in transient electromagnetic (TEM) surveys. CED is a source of alternating transverse magnetic (TM) polarized field, a surface analog of a vertical electrical line in VES. In the course of two recent decades, the method has been developed theoretically and tested through the field practice. The respective published results are expected to provide an idea of TEM soundings with the optional use of either TE or TM mode. In this paper we report some new theoretical aspects and share our field experience of surveys with an CED system.

Keywords: TEM survey; circular electric dipole; TM field; vertical electric sounding

Introduction

About three decades have elapsed since a radial current source, called "circular electric dipole" (CED) was suggested as a transmitter in resistivity surveys, besides the classical loops and lines (Fig. 1). It is a source of alternating transverse magnetic field, a surface analog of a line in vertical electric surveys (VES). Since then the method has been substantiated theoretically and appreciated for the option of choice between the transverse electric (TE) or transverse magnetic (TM), or mixed source fields. Resistivity surveys with the alternating TM make a step forward in TEM soundings toward getting rid of the "normal" signal and highlight the anomalies. Many years ago, resistivity surveys always used dc sources. Then the dc signal became an annoying background preventing the users from solving more subtle problems, and the geophysicists decided to turn the transmitters off and record the transient responses of the earth (voltage decay). Now it is clear that the classical transient response of the whole subsurface itself may become a noise component as well. The use of the TM field allows eliminating it physically, like dark glass, to bring out other signals which are either very low or have a different origin.

Thus, CED came in use as a source of the electromagnetic field, and much recent experience has been gained in operating this sophisticated transmitter system (e.g., Mogilatov, 2002). Excitation of a pure TM field requires a rigorous configuration choice for both transmitters and receivers unlike the conventional systems. In this respect, we discuss below some theoretical and practical issues of CED operation, as well as future prospects.

Definitions

Theoretically, the circular electrical dipole refers to distribution of the surface radial eddy current, with nonzero surface density (in A/m), on the circle of the radius r_0:

$$j_r^{cm}(r) = \frac{I}{2\pi r} \cdot [U(r - r_0 + dr_0/2) - U(r - r_0 - dr_0/2)], \qquad (1)$$

where $U(x)$ is the Heavyside function (on the left in Fig. 2), and azimuthally uniform radial current is grounded on circles with the radiuses $a < b$ (on the right in Fig. 2). The case of the central grounding ($a = 0$) is obviously of greatest practical importance. Furthermore, an CED can be implemented as a finite number of lines (in the middle in Fig. 2).

Such source excites the electrical (E_r, E_z) and magnetic (H_φ) components of the EM field in a 1D layered earth, in

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cylindrical coordinates, i.e., it is a source of a transverse magnetic (TM) field.

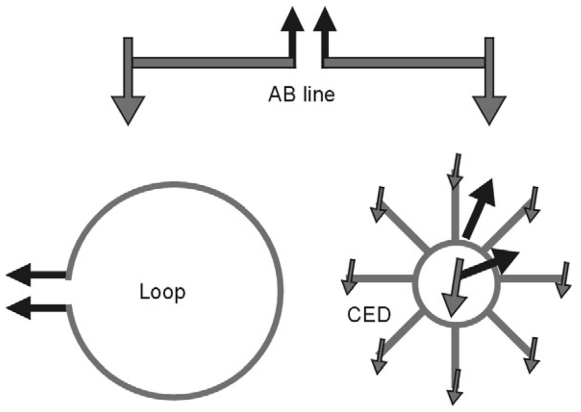

Fig. 1. Three sources for TEM surveys.

CED magnetic field

If an CED lies on the ground surface, the normal (1D) magnetic field on the surface and above it is zero. The CED is sometimes thought to lack its natural magnetic field (unlike a loop) while the magnetic field is induced uniquely by currents in the earth. However, this idea is not quite right.

In the specific case of a very large (infinite) outer radius, the current system can be considered as point-like grounding with a radial current input. The point grounding is however known (Zaborovsky, 1963) to have a magnetic field, which in the air (origin of coordinates at the grounding point, dc) is

$$H_\varphi^0 = \frac{I}{4\pi r}\left(1 - \frac{|z|}{\sqrt{r^2+z^2}}\right). \tag{2}$$

The total field in the air is zero, and the radial current has the same magnetic field but of the opposite polarity. The earth and air magnetic field of the grounding is the same (2) while the field of the radial current has a different polarity. Therefore, the total field excited in the earth by an CED source of an infinite radius is

$$H_\varphi = \frac{I}{2\pi r}\left(1 - \frac{|z|}{\sqrt{r^2+z^2}}\right). \tag{3}$$

Thus, the CED quasi-stationary magnetic field is present in a 1D earth only within conductors but fails to penetrate there when being separated by a nonconducting layer. It means that the magnetic response of a layered earth becomes fully compensated on the surface, and weak anomalous signals can be picked on this background. This may be, for example, a field of a local resistivity feature.

In a 3D modeling problem, it looks as follows. The model and contour line maps of the observed field for two magnetic flux components (Fig. 3) resolve well the anomalies in the absence of background earth responses.

This method is sometimes misrelated to the so-called pure-anomaly methods, which are rightfully infamous in resistivity surveys. The pure-anomaly methods record only the anomalous component of the total field and try to reject the latter as noise. However, the total field interferes with the observed signal, this being a pitfall of the approach. The problem can be resolved with the use of CED configured in a way to eliminate the background earth responses from all magnetic components. In this case the effect of the background is removed physically rather than by space-time filtering. Of course, precise source configuration may be problematic, but this is a matter of trade-off between the wanted 3D result and the required costs for sophisticated experimental and computing (processing) facilities.

We suggest another mental experiment to adapt the pure-anomaly approach to the CED method. In order to record the anomaly response only, one can measure the magnetic field induced by the line AB (the source) along this line. This is a line of polarity reversal, and the magnetic field is zero along it, which creates critical conditions for measurements. Furthermore, the measurements cover a small area. Adding another transmitter line counter to the first one (Fig. 4) gives zero magnetic fields already along four directions off the central electrode. Four crossing lines give already eight directions with zero magnetic fields, and eight such lines give sixteen directions of a zero background (quite a sufficient number), etc. It is important that although remaining the lines of polarity reversal, these radial profiles have a vanishing residual

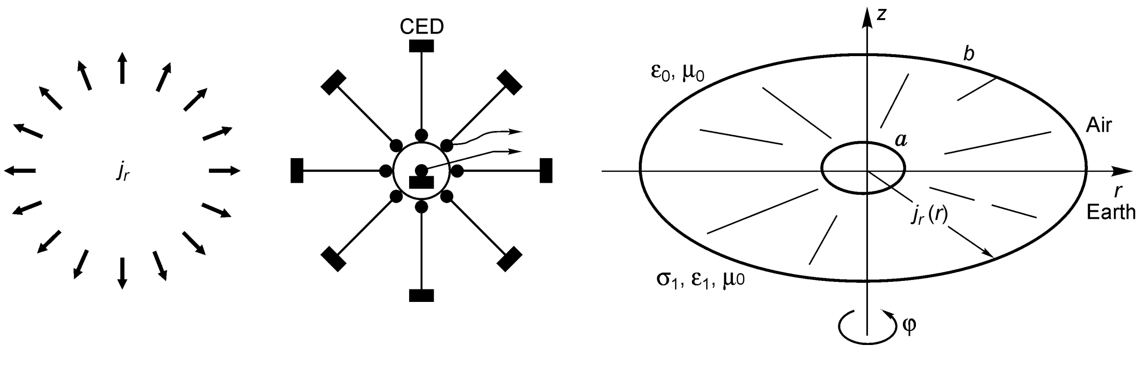

Fig. 2. A theoretical, a real, and an ideal circular electric dipole. See text for explanation.

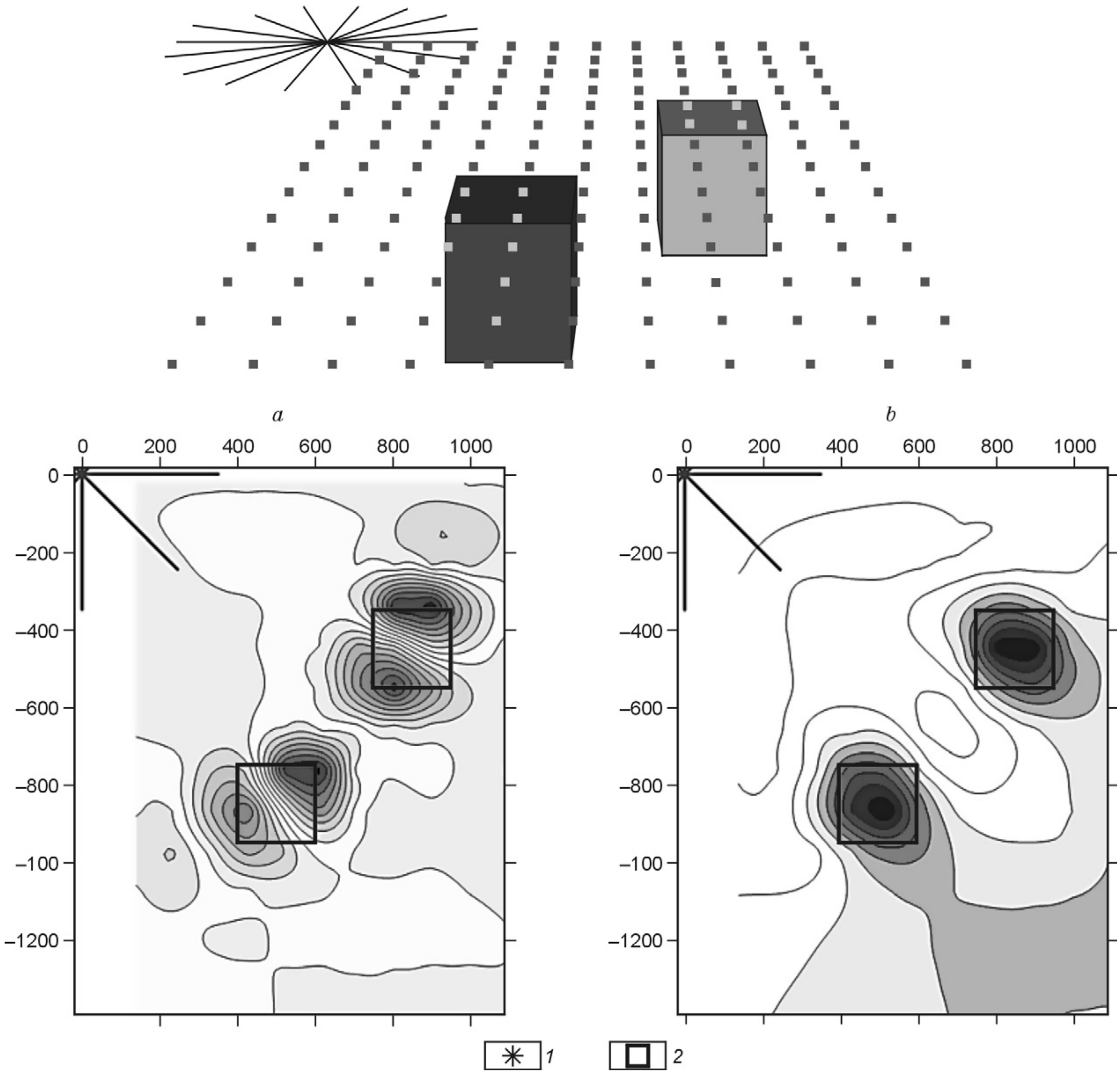

Fig. 3. 3D modeling of a CED magnetic field. Contour line maps of the observed signal: dBz/d (*a*), dB_φ/dt (*b*). *1*, CED; *2*, modeling domain.

magnetic field between them, which allows setting up areal measurements of the total field corresponding to anomalous responses. Thus we depart from the pure-anomaly method and arrive at an CED transmitter.

CED electric field

The CED electric field has the components E_r and E_z (in cylindrical coordinates) in a 1D earth and a single normal 1D E_r component on the surface, which can be recorded using a source of a TM polarized field, such as CED. The properties of the TM polarized field from an CED source (Mogilatov, 2002) are unusual for the resistivity surveys which commonly employ the TE polarization. In this study though, we confine ourselves to the effect of a thin high-resistivity layer. The TM field is especially sensitive to such layers, with may be an advantage if they are the survey targets (e.g., reservoir rocks) or a drawback if they overlie and screen the target layers. In dc surveys, the underlying section obviously becomes irresolvable, but the situation is more complex in harmonic or TEM surveys. It is impossible to apply the quasi-stationary approximation inside the insulator because eddy currents have to be taken into account. In the conventional TE surveys, the eddy current effect is always vanishing, and the problem is thus resolved.

However, the problem arises again with a pure TM field. Modeling with regard to eddy current for the case of an insulator (Fig. 5) has led to a striking result, as it often happens in analysis of the TM field behavior. The responses affected by eddy currents turned out to be strongly controlled by the subsurface resistivity, which was proved valid by further calculations. See two voltage decay curves compared in Fig. 5: one corresponds to quasi-stationary exponential

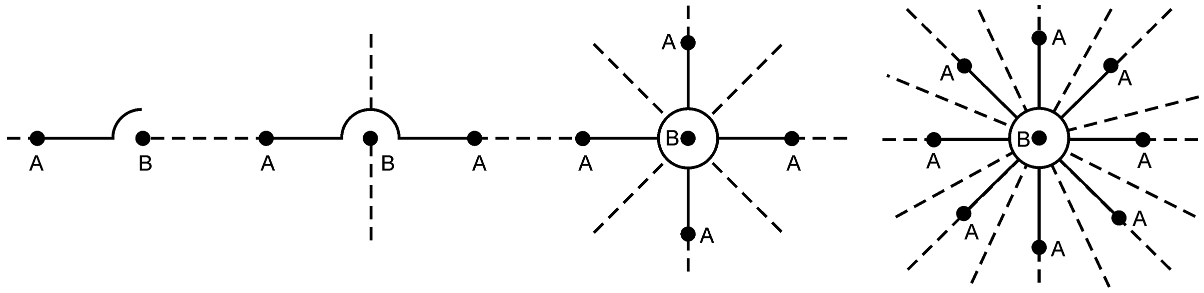

Fig. 4. Zeroing of the 1D normal background.

decay defined by the surface layer only and the other curve is obtained taking into account eddy currents. Note that our modeling results (Fig. 5) found support from independent finite-element calculations (by M. Persova).

Circular and vertical electric dipoles

An CED source was originally interpreted as a surface analog of a vertical electric dipole (VED), which placed it into a familiar context. This is essentially true as both vertical and circular electric dipoles excite only electric field with similar spatial patterns of toroidal currents in the earth (Fig. 6*a*).

As it was shown earlier (Mogilatov, 1996; Wait, 1997), the harmonic field of an CED source on the surface and the field of a VED source placed at the depth h are described by the same vector potential equation if $h \ll r$, $|k_0 r| \ll 1$ and $|\hat{\sigma}_1| \gg \varepsilon_0\,\omega$ $(k_j^2 = \mathbf{i}\omega\,\hat{\sigma}_j\,\mu_0,\ \tilde{\sigma}_j = \sigma_j + \mathbf{i}\omega\,\varepsilon_j)$:

$$A_z = \frac{C}{2\pi}\cdot\frac{z}{R^3}\cdot(1 + k_1 R)\cdot\exp(-k_1 R), \qquad (3)$$

where $R = \sqrt{r^2 + z^2}$ and the coefficient $C = Idzh$ in the case of VED and $C = I_0\, b^2/4$ in the case of CED.

However, as Wait (1997) noted in his comment to our paper (Mogilatov, 1996), both CED and VED should behave as quadrupoles according to equation (3). The CED source is a "true" quadrupole while the VED field becomes quadrupole near the ground surface. It was even suggested to use the term Central Electric Quadrupole (CEQ) instead of CED, which appears hardly reasonable though from the practical point of view.

Nevertheless, the analogy between CED and VED is very stable being relevant to the layered earth and to the transient process as long as the two sources lie on and near the ground surface, respectively. For instance, the late-time responses ($t \to \infty$) of a two-layer earth with a resistive layer below to both CED and VED excitation are (Mogilatov, 2002):

$$E_r(t) \approx C\cdot\frac{r}{\pi\sigma h^5}\cdot\left(\frac{\mu_0\sigma h^2}{2t}\right)^2\cdot\exp\left(-\frac{\pi^2 t}{\mu_0\sigma h^2}\right), \qquad (4)$$

where C for the CED and VED sources are as specified above.

The situation becomes different, however, when the two sources are placed offshore in deep sea: the VED field becomes dipole (Wait, 1982):

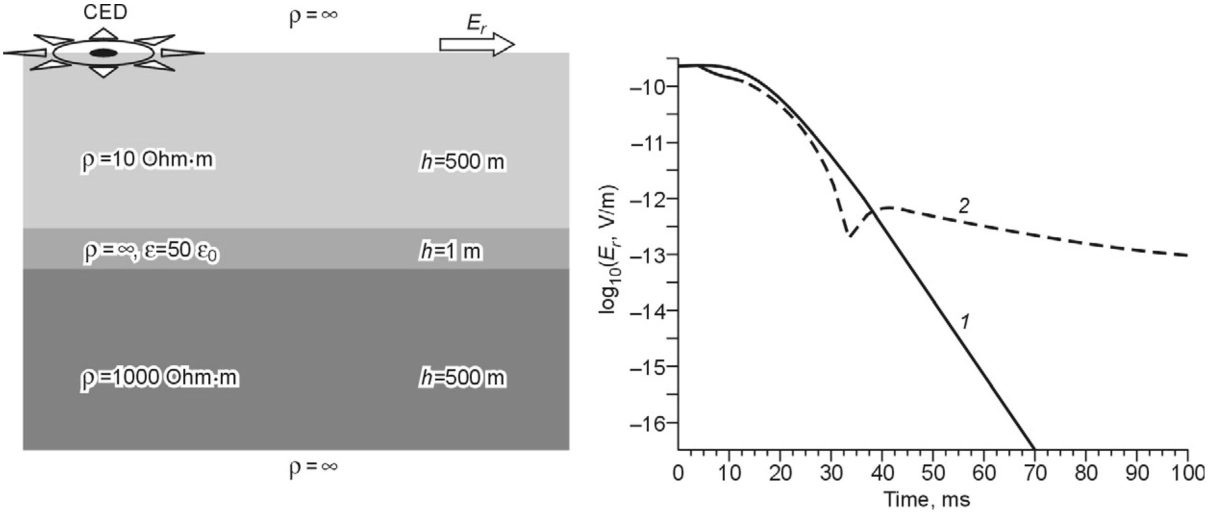

Fig. 5. Eddy currents playing an important role in the case of a TM field. Solid line *1* is quasi-stationary approximation, dashed line *2* is a curve taking into account eddy current.

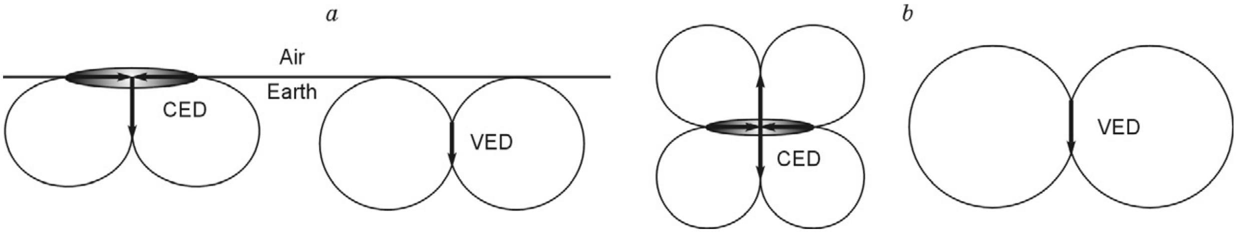

Fig. 6. Onshore (*a*) and offshore (*b*) CED and VED toroidal systems.

$$A_z = \frac{Idz}{4\pi R} \cdot \exp(-k_1 R), \tag{5}$$

while the CED field remains quadrupole (Fig. 6*b*). The VED source forms a single toroidal system of currents and CED forms two such systems (an upper and a lower ones). Therefore, the submerged CED and VED have markedly different properties, especially during the voltage decay. Namely, the CED field shows complex behavior associated with the evolution and interaction of two toroidal systems of secondary currents.

Real and ideal CED

The CED transmitter system can be implemented in different ways depending on size. A small system may be a metal disc or an array with grounding at the center and along the margin. However, the latter being difficult to provide, it may be better to refuse the external grounding at all in the case of high-frequency shallow soundings. On a large scale, an CED source may be made as evenly distributed radial lines, commonly a radial system of eight current rays. It is important to compare such a field system and an ideal source, leaving aside the technical problems of precise geometry and current equality of the rays. It is a serious question because the real and ideal CED sources actually differ in terms of the TM-TE approach: the ideal CED by definition excites a TM field while the field of the real radial source of eight rays additionally bears a residual TE mode. It is obviously quite large at early times near the source and may be expected to be smaller than the TM mode at late times. However, the TE mode has a longer decay time and will prevail at the latest times, though both theory and practice show it to be vanishing over a large range of times used in the field. The induction component may be notable in some cases, especially in mineral exploration and has to be accounted for at early times by 1D forward modeling. In Fig. 7 we compare three voltage decay curves for a radial electric gradient corresponding to an ideal and an eight-ray real CED systems, as well as a response bearing the residual TE mode. The ideal and real CED curves coincide in this example, but generally the approximation quality depends strongly on the system size, on the earth resistivity pattern, on the bandwidth, as well as on the acquired component (magnetic or electric). Therefore, the solution is to have interpretation software with the respective algorithms for ideal and real CED sources in specific resistivity settings, which are applied to survey design and data processing, like those used in the case of Fig. 7.

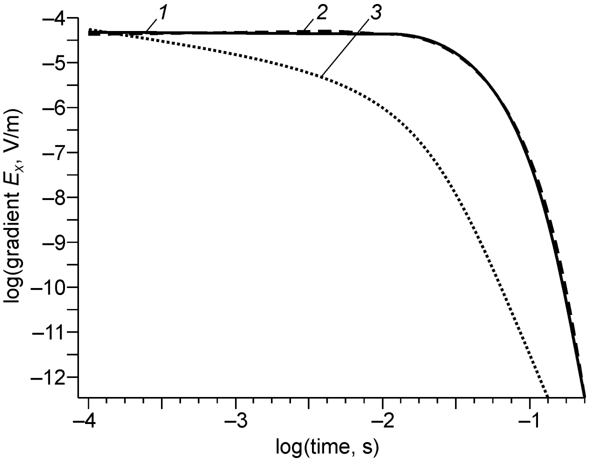

Fig. 7. An ideal (solid line *1*) and a circular (dashed line *2*) electric dipoles, and the residual TE field (dotted line *3*).

Of course, such a sophisticated system as CED is designed basically to excite a TM-polarized electromagnetic field, but it offers also various additional options of configuration management by varying current in the rays. Thus obtained datasets allow improving the inversion quality, as it was in the case of soundings we performed with transmitter lines oriented in different directions.

Defects in the field CED configuration

Above we compared an ideal source and a perfectly configured eight-ray CED system with rays of equal lengths, orientations angles, and currents. However, the configuration is never perfect in the field, and the errors may appear afterwards in measured data. It is possible to estimate the influence of different defects and to take in into account by considering an CED as a set of current lines. Although CED sources are commonly used to study 3D structures, the configuration defects can be estimated in 1D modeling. The typical defects are related to inequality of ray currents, lengths, and angles. The current error may be due to miscalibration in the management and control unit, which is equivalent to the presence of a grounded line with small current (defect current) making an additional source besides the "right" CED. The length error is equivalent to the presence of an additional short current line (defect length) besides the "right" CED.

Note that the use of CED requires precise system geometry (sizes) and current equality imposed by the very physical phenomenon of the TM field polarization. However, the large survey experience, including 3D soundings, shows that the toroidal system of secondary currents is stable enough due to interaction between the electric and magnetic components.

Effects of terrain and earth resistivity patterns

The survey results always depend on the terrain. If no question of terrain effect arises in some method, it means that the method is rough. In the CED surveys, the effect of terrain is analyzed by numerical modeling, though it can be neglected since some sounding times. Of course, the importance of terrain effects depends on the size and contrasts of the target. Once we had to apply a terrain correction to all measured times because of a badly positioned source.

Another problem may result from different geometries of earth layers. In the case of poorly contrasting objects, the effect of general uplift (subsidence) on the signal shows up after some time. The responses of uplifted layers are well pronounced in the component as signal splitting, stable in time, into positive and negative antisymmetrical parts, with the axis across the CED center. This effect can be eliminated after modeling, and sometimes it does not impede the detection of local objects.

Finally, there is a specific case of earth heterogeneity which may happen in practice (and happened indeed). Namely, it is high noise from a buried metal pipeline in the CED vicinity, especially if the pipeline lies along a radial direction relative to the CED center. This noise acts as an additional strong field source which never stops at the onset of acquisition.

Note also that the pure TM polarization is possible in a horizontally layered earth only. On the one hand, earth is never perfectly layered but, on the other hand, there always exists an apparent (effective) layered section that represents the background conductivity. This background response is never present explicitly, but the acquired data store record of various deflections from this ideal layered model and thus are to be sorted and interpreted in 3D. However, unlike the conventional TEM case, these procedures are applied to the compensated conductivity responses.

Field measurements of the electric component

The surface CED electric field is "normal" or background (1D), being the E_r component in the cylindrical coordinates. Measurements by a radial receiver line allow layer-by-layer interpretation, but it is strongly limited due to sensitivity of the electric signal to resistivity heterogeneity, for the following reason. The E_r background (as a component of the TM field) decays faster than the anomalous responses of resistivity features, which are induced by secondary horizontal currents and are controlled by the long-lasting TE field. Therefore, electrical measurements can complement those by magnetic receivers of CED signals to better resolve local 3D features. Such surveys were carried out recently in the kimberlite fields of Yakutia. Furthermore, 3D modeling of marine data show the anomalous magnetic field to be too low, while the electric signal is rather high and contains a well detectable anomalous component.

There is another pitfall, which likewise can be turned into an advantage: the CED electric signal may bear a strong IP effect (again, because of rapid voltage decay). In this respect, IP measurements may be even more efficient than with the conventional ABMN system.

Prospects and projects

Electromagnetic surveys with the CED source remain of limited use, and not all advantages of the alternating TM-polarized field have been employed yet. For instance, CED is in fact a pulse source, which can be "eliminated" during measurements. However, this is of minor importance in the case of magnetic responses to CED signals because the direct field is compensated even in the harmonic regime. The use of a frequency mode would simplify the power unit.

Then, grounding the outer ends of the radial lines is unnecessary at high frequencies (or at the earliest times), this being a prerequisite for efficient near-surface (dielectric?) soundings.

TM-field sounding may be also useful in marine resistivity surveys. Seawater produces large noise in the data of conventional sources where the magnetic mode predominates. CSEM is the only known case of successful soundings in which a long-offset ABMN system can resolve a high-resistivity target because the seawater attenuates the background field. However, it works only at water depths below 1000 m and offsets about 15 km. The use of CED may help the situation because the TM field does not depend on the total conductance at any times and is sensitive to high-resistivity objects irrespective of the sea depth.

There is a marine geophysical application of CED where the problem of deployment and transport of the complex system is resolvable. We mean the Arctic project in which the huge CED system deployed on perennial ice drifts like the North Pole stations (Fig. 8). The system consists of fixed electrical receivers as horizontal and vertical lines grounded in the water, as well as an array of portable sources of magnetic field. The measurements may be either continuous (which is hardly feasible) or repeated every few days at a certain point (assuming the drift velocity 5–7 km per day). The problem requires further studies, but anyway such surveys can cover a strip of ten radiuses wide along the source path, or an about ~600,000 km^2 corridor (given the 15 km CED radius and the total drift distance 4000 km, corresponding to the average for Soviet polar stations).

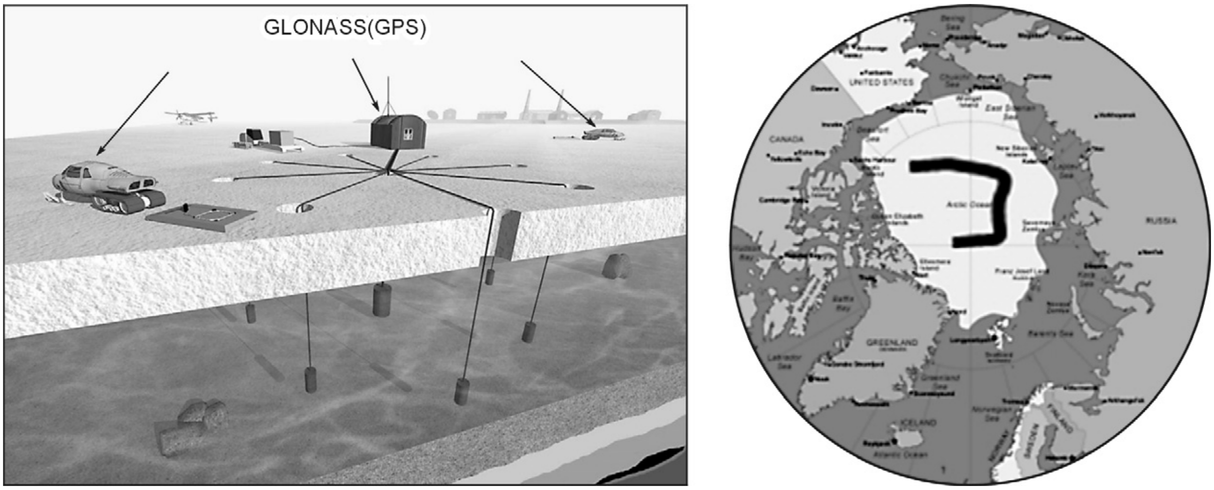

Fig. 8. Arctic project.

Conclusions

The CED sources have been in use for electromagnetic soundings for two recent decades. The gained experience has shown that the preference the theory gives to this source of the TM field (as well as to the vertical electric dipole) can find a reliable and universal practical realization different from that of VED. It means creation of a new line in resistivity surveys that can comprise several methods. The use of CED has a sound theoretical background corresponding to the properties of the TM field; there is also a practical aspect of compensating the background (1D) magnetic response on the surface, which is very important but has not been fully appreciated yet. It allows high-density 2D recording of signals from a fixed source to detect inferred objects or discover unknown effects in the observed field, actually without any interpretation, using reliable and detailed 2D and 3D images.

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