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POORLY STUDIED PHENOMENA IN GEOELECTRICS

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Undoubtedly, modern geoelectric technologies emerge in the result of the development of traditional approaches and techniques. However of more interest is the appearance of completely new technologies based on new effects and new models of interaction of geological medium and electromagnetic field. The author does not commit to indicate principally new directions, but only wants to discuss some poorly known facts from the theory and practice of geoelectrics. The outcome of this study could be considered attracting the attention of experts to non-traditional signals in geoelectrics. The reviewed phenomena of interest, not fully implemented in practice in the author's opinion, are field split into two polarizations: transverse electric (the TE-field) and transverse magnetic (the TM-field), then some poorly known properties of TM-field, the role of bias currents, the anisotropy of horizontal resistances, the role of geomagnetic field in geoelectric sounding, the unique resolution of CSEM (Controlled Source Electro-Magnetic) techniques at sea.
Key words: geoelectrics, transient processes, TM-polarizations, the Lorenz effect, the bias currents, anisotropy, CSEM.

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Introduction. Undoubtedly, modern geoelectric technologies emerge in the result of the development of traditional approaches and techniques. However of more interest is the appearance of completely new technologies based on new effects and new models of interaction of geological medium and electromagnetic field. Using the example of things known in general but not too widely recognized the author tried to point to possibilities of progress in different directions.

Personal experience of the author indicates that one might expect some new phenomena in case the very type of electromagnetic forcing on the geological medium is changed. Due to 1D dimensionality of the base horizontally homogeneous model of the medium in geo-electrics with controlled sources there takes place a split of the common geo-electromagnetic field, i.e. each component of magnetic and electric field is split into the TM- and TE-components or polarizations (Transverse Magnetic and Transverse Electric). The following terms are used: TM- and TE-field, transverse-magnetic and transverse-electric field, *E*- and *H*-modes, field of electric type and field of magnetic type, galvanic and induction field (e.g., [2]). J.R.Wait was the first to bring everybody's attention to completely different properties of these components of the field of arbitrary source back in 1986 [11] while assessing the sensitivity of techniques to detecting a thin high-Ohmic horizon. Such a split enables one to have an effective simple theoretical description while having a deep link to the type of feeding installation. Such a well-known source as current loop at the daytime surface or the one in a different horizontal plane generates a TE-field only. A well-known source that generates a TM-field only is an impractical vertical electric dipole (VED or a VEL line). Another traditional source is a horizontal electric dipole (HED or HE line, HEL) that generates a mixed field in which the TE-mode prevails though.

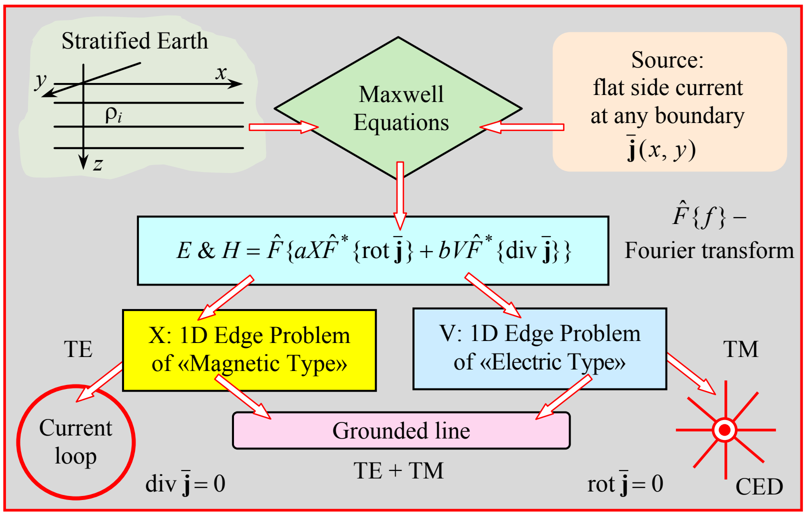

Fig.1. Conditional physical and mathematical model of geoelectrics. Splitting intoinputs by TE- and TM-polarizations of the total geo-electromagnetic field (*E* and *H* components) of arbitrary distribution of side current in horizontal plane (flat side current)

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The physical-mathematical model of induction geo-electrics with controlled sources, presented conditionally in Fig.1 (and founded in detail in [2]), is biaxial and symmetric with respect to the fields of electric and magnetic types. The theory is far from new, it is just a scheme that reflects properly the dual (TE-TM) nature of geo-electromagnetic field. It points directly to the existence of a source of electromagnetic field of electric type, symmetric to the familiar current loop in a sense: a circular electric dipole (CED), presented in Fig.1 as an absolutely natural addition to the basic geoelectric sources, the current line and loop. However that scheme is not implemented in practice, the properties of alternating TM-field are studied poorly, and the ground source of alternating field of electric type was not known. Modern induction geoelectrical prospecting (pulse, in particular) is practically based on using the field of magnetic type only. It is generated by induction (e.g., by the loop), and generally the discussion covers induction geoelectrics only. The approach based on the «TE-TM-dualism» to theoretical description, development of technical means and practics of geoelectrical prospecting using controlled sources is the topic and techniques that we pursue here.

TM-field properties. First of all, one has to understand that TM-field is a radically different way of existence of electromagnetic field in stratified Earth and a different mode of interacting with it than the habitual TE-field. Fig.2 demonstrates conditionally the systems of generated currents under TE-polarizations and TM-polarizations – the famous “current ring” formed by horizontal currents and the toroidal system of currents featuring a vertical electric component. The first one is generated by the current loop, the second – by the vertical electric dipole, the circular electric dipole and the point grounding. The point is that the properties of TM-field are completely different from those of TE-field, the latter commonly known and perceived as the general features of the transient process of field formation. The transient TM-field may only follow an exponent; the only indicator that the field does not depend on is cumulative longitudinal conductivity; meanwhile it always depends on the vertical structure of the medium, depends on the shape of generating current pulse at every stage of the process, is associated with anisotropies and is very tightly linked to the polarization induced parameters (PI); meanwhile it has no magnetic response on daylight surface. The last property is very important: we gain a possibility to get rid of powerful generalized background produced by host rock and may record weak signals, sometimes of a new nature [2].

Bias currents. The fact that the traditional induction geo-electrics employs the TE-polarization field entails a somewhat limited outlook on geoelectrics as a whole. For example, the notion is quite popular that bias currents play no role in deep layers geoelectrics [6]. However, that is only true with respect to the TE-field. Meanwhile the situation is completely different when the TM-field is employed. We did calculations for the transient processes (following the classical technique in the «frequency domain» [1, 2]) with the account of bias currents for the model with a thin insulation horizon, presented in Fig. 3, EM field generated by a circular electric dipole, and, as it happened many times during the analysis of the behavior of TM-field, the obtained result was amazing. Fig.3 compares two transient curves (the radial gradient of electric field E_r at daylight surface for a spacing of 1500 m, and CED current of 1 A). The first one is quasistationary ($\varepsilon = 0$) and is defined by the upper layer only. The downtrend is exponential. The second curve ($\varepsilon = 50\varepsilon_0$) demonstrates the effect of bias currents: change of sign and a slow power-law drop-off by the end of the transient process. This influence is quite critical.

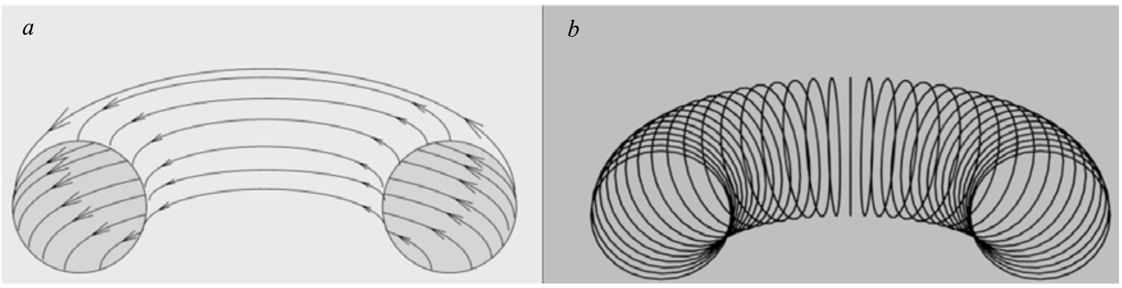

Fig. 2. The system of horizontal currents: field of magnetic type (*a*), toroidal system of currents: field of electric type (*b*)

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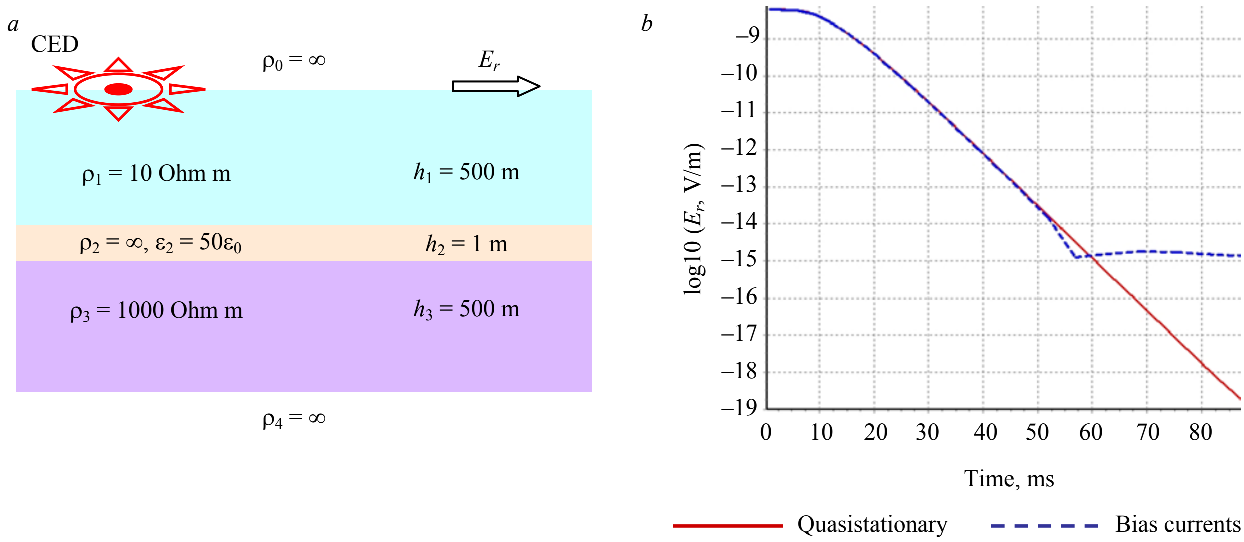

Fig.3. Model of the medium (*a*) and the transient curves (*b*). The «Quasistationary» curve gives the results of solving the quasistationary problem, the "bias currents" curve gives the same with the account of bias currents (E_r)

These results obtained by the numerical implementation of the variables separation technique were rather unexpected, and additional test calculations were needed to by the finite elements technique [10]. In addition to that we also derived an asymptotic formula for a late phase (using the Tikhonov's technique in the «temporal domain» [5]):

$$E_r = \frac{I r_0^2 r}{16\pi} \frac{\rho^3}{h^3} \frac{\varepsilon^2}{\delta h^2} \frac{1}{t^2},$$

where the resistances and depths of the upper and lower layers are identical to each other (ρ, h); δh is the depth of the insulation layer.

Thus the result in Fig.3 was thoroughly tested. Further calculations (also pretty non-trivial [10]) demonstrated a sharp dependence on the resistance of the lower layer.

Geomagnetic effect. The transient secondary currents generated by controlled sources take place in the magnetic field of Earth. This geomagnetic field (~50 A/m) is several thousand or even dozens of thousand times higher than the secondary magnetic fields generated in the course of transient sounding (TS). However, as far as the author knows, its effect on the transient process itself was never discussed. That seems to be quite strange. There is a branch of physics studying the motion of charged particles that form the current in crossed electric and magnetic (external) fields. What is meant is the Lorenz effect and the galvano-magnetic effects (e.g., the well-known Hall effect). The compass arrow rotates in the Earth magnetic field. That is a fact that everybody knows. The system of secondary currents inside the Earth also features a magnetic moment and should react to the Earth magnetic field (Fig.4).

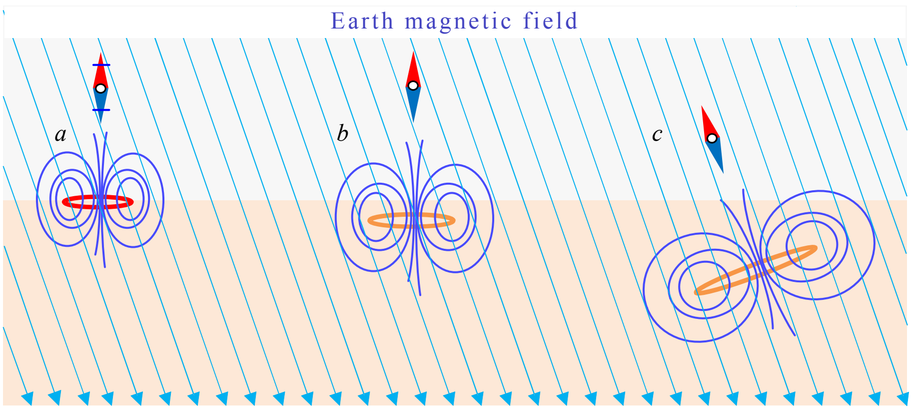

Fig.4. Interaction of magnetic dipoles with the Earth field: *a* – current in the loop is not switched off (the analogue of a fixed magnetic arrow); *b* – current in the loop is switched off and there formed a secondary current ring in the Earth (magnetic arrow is freed); *c* – magnetic dipole rotates in the Earth magnetic field (same as a magnetic arrow)

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Model of the medium

Layer number	Thickness, m	ρ_x, Ohm m	ρ_y, Ohm m	ρ_z, Ohm m
1	200	5	5	5
2	100	0,1	1	5
3	∞	100	100	100

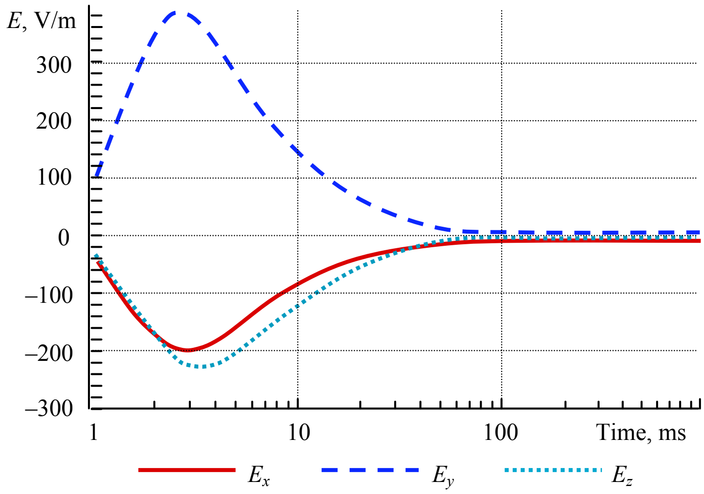

Fig.5. Transient curves of electric components E_x, E_y, E_z

Even the very superfluoustheoretical analysis demonstrates the following. First, geomagnetic effect results in some effective (seeming) anisotropy (the Hall anisotropy) and vertical magnetization of the initially isotropic non-magnetic medium (geomagnetic effects of the first and second type). Second, geomagnetic effect is very tightly connected with the substance composition of the medium and its microstructure. Third, it seems that the theory is quite far yet from yielding reliable quantitative assessments and will have to lean on experimental facts anyway. Therefore one would rather follow the experimental approach in assessing geomagnetic effects in the TS.

In author's opinion some facts are available already that point to manifestations of geomagnetic effects in geoelectrics. These are some cases, known to the author, of correlation between the data from geoelectric transient sounding and geographic orientation of the installation. Of course, perturbations are not large and may easily be explained away by the properties of geological medium (lateral anisotropy). However, silencing that issue may complicate progress in geoelectric studies. Geomagnetic effect may be considered as a hindrance that should be accounted for. However, we believe the point is different. Nature offers us some extra possibilities for in depth studies of geological medium with electromagnetic techniques. A more detailed presentation of the issue may be found in [3].

Anisotropy of horizontal resistances. Applied studies in electromagnetic logging and geoelectric exploration the medium is assumed either isotropic or featuring a common anisotropic conductivity. Meanwhile, there are many indications that the medium may even feature biaxial anisotropy, i.e. resistances may be different in all three directions, *X*, *Y and Z*. Obtaining a theoretical solution separating the variables and its numerical implementation is associated with certain difficulties in that case [4]. Results were obtained interesting from the geoelectric point of view, e.g., the appearance of a vertical electric component of the field while exciting a horizontally stratified cross-section with a vertical magnetic dipole.

The table accompanying Fig.5 presents a 3-layer cross-section, its middle layer featuring a biaxial anisotropy. The source was a vertical magnetic dipole with a moment of $M_z = 1013\ \mathrm{A{\cdot}m^2}$, located at the daylight surface. Observations were taken at the depth of 200 m, i.e. at the second boundary, the point coordinates being $x = 200$ m, $y = 200$ m (since vertical resistances are equal, it makes no difference whether the sensor is above or beneath the boundary). The time range of recording the response is from 1 ms to 5 s. Fig.5 presents the curves of transient processes for all three components of electric field. One may see that the vertical component that is absent in common media, either isotropic or featuring a single-axis anisotropy, is quite comparable to the horizontal one in this case.

CSEM (Controlled Source Electro-Magnetic). One would like to point out another phenomenon too, the unexpected effectiveness of the CSEM technique in deep sea (a paradox in itself!) (e.g., [7, 8, 10]). That effectiveness, manifested by the submerged ABMN unit with respect to items of higher resistance, is easily confirmed by theoretical calculations and remains somewhat sustainable in practice. The CSEM technique is more than a decade old already, and it has given birth to a whole new direction generating enormous amount of publications in the West, where it is considered the most important application for geo-electrical studies with controlled sources. Within that time frame multiple explanations

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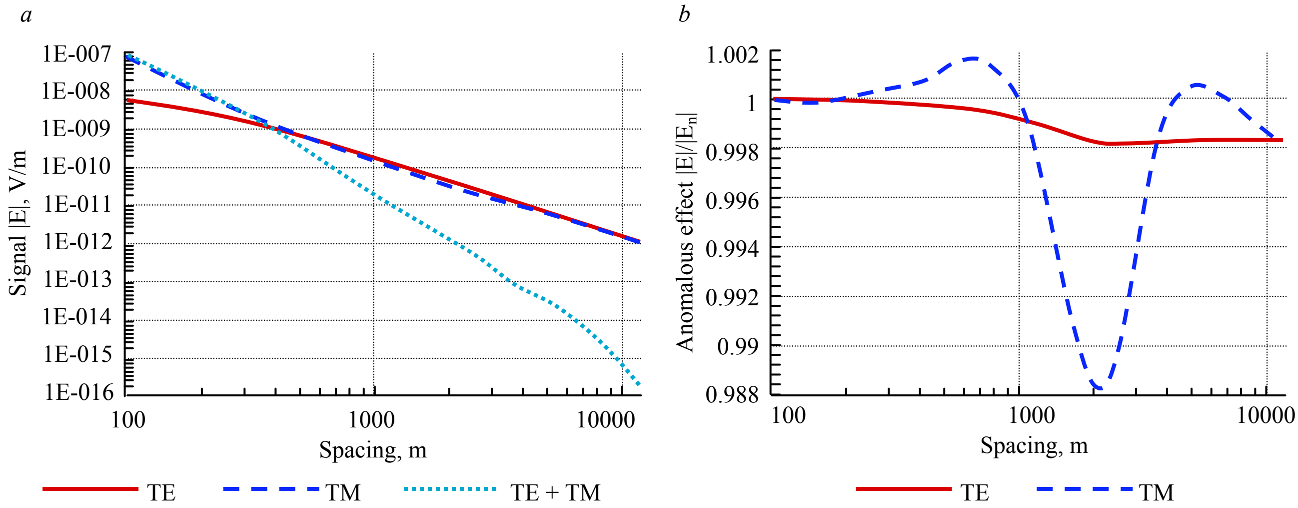

Fig. 6. Inputs by TE and TM-modes to cumulative signal: *a* – separate modes and cumulative field (amplitudes), legend: TE – input by TE-mode, TM – input by TM-mode, TE + TM – cumulative field; *b* – relative anomalous effects in TE- and TM-modes (amplitudes), legend: TE – ratio of TE-mode values to TE-mode in case of normal field (no target), TM – ratio of TM-mode values to TM-mode in case of normal field (no target)

were suggested of the effectiveness of the technique (e.g., «waveguides»), but lately the tradition shifts to discussing absorption of the TE-mode in deep sea and sensitivity of the TM-mode to a «resistive» target. One may agree with that in principle, save making one further update. Assume a «standard» model: sea water ρ = 0.3 Ohm·m, h = 1000 m, host rock below sea bottom (ρ = 1 Ohm m) with study target at the depth of 1000 m under that bottom (ρ = 100 Ohm m, h = 100 m). The ABMN unit is functioning in its harmonic mode (current 1 A, frequency f = 1 Hz) changing its spacing to 12 km. We calculate the response signal, plus the TE- and TM-mode, each separately.

Fig.6, *a* presents the respective curves (amplitudes in log scale) for the modes and the cumulative field. Modes practically coincide for large spacings, while the cumulative (TE + TM) signal results from deep mutual compensation of the modes (they enter the total signal with opposing signs). The cumulative field is several orders of magnitude lower, with results in major anomalies. Fig.6, *b* presents such anomalous effects produced by the «resistive» layer in each of the modes. Low scale of such effects (shares of a per cent) draws one's attention, and it may be pointed out too that it is the deep mutual compensation of the modes which turns such weak effects in separate modes into a gigantic (up to 10,000 %) effect with respect to the cumulative field. One sees too that the anomalous effect from the «resistive» layer is way larger in the TM-mode, which seemingly agrees with common understanding. However, one finds that the anomalous effect in the cumulative field is mostly formed by the TE-field in the range of large spacings (exceeding 5,000 m). Now, that is somewhat unexpected. One is forced to recollect the «waveguide» hypothesis. We have no waveguides in our case though, the situation is quite quasi-stationary, but one may speculate about the propagation of TE-mode along the high-ohmic horizon.

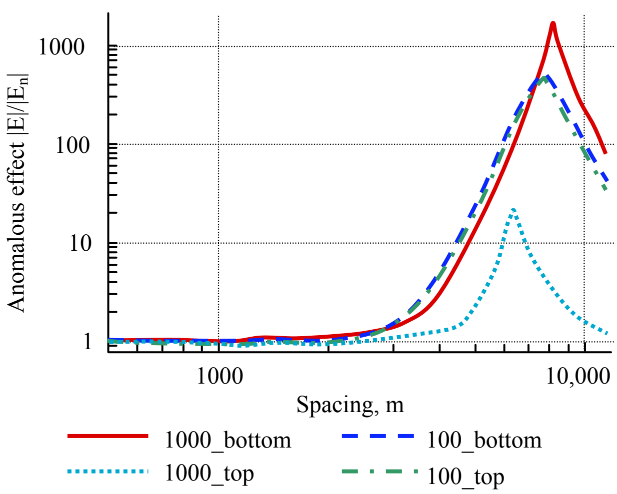

Fig.7. Total field E_r CED to normal field ratios (the anomalous effect). Curves legend: 1000_bottom and 100_bottom are CED at sea bottom, depth, respectively, is 1000 and 100 м; 1000_top and 100_top are CED at sea surface, sea depth being 1000 and 100 m, respectively

So, the situation with CSEM technique is quite peculiar. The principal lesson for all the other geoelectrics consists in the need to achieve the maximum compensation of normal background signal, thus producing a high anomalous effect.

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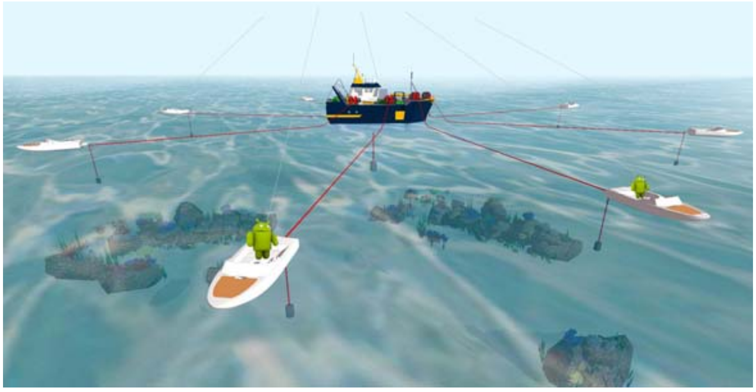

Fig.8. Marine CED unit

Employing the TM-field we may offer a technique sensitive to high-Ohmic and also low-Ohmic anomalous targets, a technique of higher resolution that does not depend radically on sea depth. Below we demonstrate that using the same model as above (see Fig.1). Consider a CED unit with the radius of 500 m operating in harmonic mode at the frequency of 1 Hz.

In our calculations we assumed sea depth of 1000 and 100 m and placed the CED unit at the bottom and the daylight surface (Fig.7). The anomalous effect was strong, not weaker than the one with CSEM. The only difference is that when CED was placed at sea surface 1000 m deep, the anomalous effect dropped to 2000 %, which is not too small either. Spacings in this example are quite large, of course. However, as demonstrated in [10], one may limit oneself to smaller spacings in transient mode, specifying the target boundaries accurately along the lateral.

It appears that the circular electric dipole, «floating» at the sea surface fits our needs quite well in every case (both deep and shallow sea), if one recalls that it is practically unlimited in its size and output power. It also means that 70 % of the surface of the globe is accessible for effective uniform electromagnetic sounding. As for its technical implementation, one may easily picture an operative CED installation using eight robotic buoy-motorboats that reel floating cables off the winches on board the core ship and then set and maintain the satellite-controlled position of such electrodes (Fig.8).

Another interesting application of CED, that waives objections against such a source, too complicated from the traditional point of view, consists in positioning a large CED installation on a perennial ice flow drifting across the Arctic Ocean.

Conclusion. Even going by the limited experience of the author only it appears that it is too early to start speculating about the “end of history”. It is also too early to reconcile to the humble role of geoelectrics and artificial sources in geophysical practices. We have not even tapped on all the possibilities implicated within the scope of absolutely classical theory of transient sounding. Optimizing one’s scheme of experiment involving the TM-field we would finally become able to employ complex models of geological medium.

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