Russian Geology and Geophysics © *2020, V.S. Sobolev IGM, Siberian Branch of the RAS*
Vol. 61, No. 10, pp. 1187–1195, 2020 *DOI:10.15372/RGG2019130* *Geologiya i Geofizika*

Theoretical and Methodological Substantiation of Transient Electromagnetic Sounding from the Arctic Drift Ice

V.S. Mogilatov[a,b], **P.S. Osipova**[a,b,✉], **A.V. Zlobinsky**[c]

[a] *Trofimuk Institute of Petroleum Geology and Geophysics, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

[b] *Novosibirsk State University, ul. Pirogova 1, Novosibirsk, 630090, Russia*

[c] *OOO Nauchno-Tekhnicheskaya Kompaniya Zavet-Geo, ul. Voskhod 26/1, of. 56, Novosibirsk, 630102, Russia*

Received 21 January 2019; received in revised form 15 April 2019; accepted 22 May 2019

Abstract—Marine geoelectromagnetic sounding with artificial sources is strongly hindered by the influence of a conductive seawater layer. There is only one known wide successful application of electrical prospecting in this field – Controlled Source Electromagnetic Method (CSEM). However, this method has unfortunate limitations: the need to submerge an electromagnetic probe to the bottom of a deep (more than 1000 m) sea and the great rafting (~15 km). The method is not applicable in an ice-covered sea. Deep sounding from the sea surface and, hence, from the ice surface is possible if the TM polarization field is used. This field is generated by a vertical electric line (VEL) or a circular electric dipole (CED). The former has drawbacks even when it is used at sea. At the same time, a CED is efficient in one-dimensional and three-dimensional media in frequency and time modes. We have developed a three-dimensional mathematical tool for the CED field in the Born approximation, which is quite adequate in a conductive section with deep local inhomogeneities. The research is carried out within the framework of a geophysical project using the Arctic drift ices.

Keywords: marine geoelectromagnetic sounding; drift ice; circular electric dipole; vertical electric line; Born approximation; Arctic

INTRODUCTION

It is well known that marine geoelectromagnetic soundings with artificial sources, especially transient sounding (TS) methods, are greatly hindered by the influence of a conductive seawater layer. This is the main fundamental difficulty of marine electrical exploration. There is virtually only one widespread successful application of electrical exploration – Controlled Source Electromagnetic Method (CSEM) (Constable and Srnka, 2007; Constable, 2010). However, the method has unfortunate limitations: firstly, the device should be submerged to the bottom of a deep (more than 1000 m) sea and secondly, the great rafting (up to 15 km). In a sea covered with ice, this method is not applicable either.

We can propose a TM field based technique that is sensitive to high-resistivity and low-resistivity anomalous objects, more detailed, and not radically dependent on a sea depth. Moreover, it is shown below that the effectiveness of this technique does not decrease if the device is located on a sea surface, which is the requirement for sounding from drift ice. This can be preliminarily illustrated using the model of a medium in Fig. 1, which is often used in CSEM. The object is a high-resistivity thin layer located at a depth of 1000 m below the bottom. The TM field is excited using a circular electric dipole (CED) with a radius of 500 m, operating in harmonic mode at a frequency of 1 Hz (as in CSEM).

In the calculations, we examine a sea with depths of 1000 m and 100 m and place the CED on the bottom and on the day surface. The results are presented in Fig. 1 in the form of an anomalous effect: the ratio of the total field to the normal field (no bed-object). Here we follow the tradition of CSEM, but it should be noted that such large values of the anomalous effect indicate that the normal field is small, so, measuring the total field, we actually measure the anomalous field. And it is quite measurable.

Thus, the anomalous effect is large, no worse than in CSEM. Only if the CED is placed on the surface of a 1000-m sea, the anomalous effect drops to 2000%, but this also confirms that the influence of the enclosing sequence is almost completely compensated and negligible. The rafting in this example is, of course, great. But, as shown in (Goldman et al., 2015), when it comes to transient from the CED, it is possible to use small rafting and accurately determine the boundaries of the object along the lateral.

So, in the case of electromagnetic soundings from the ice surface in the Arctic and prolonged ice drift, the use of a

✉ Corresponding author.
E-mail address: osipovaps@ipgg.sbras.ru (P.S. Osipova)

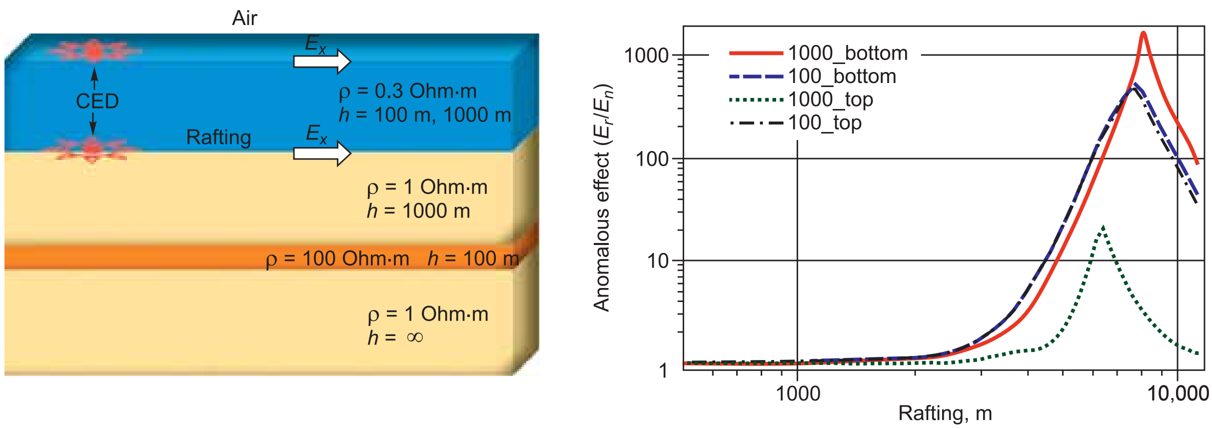

Fig. 1. Curves reflecting the ratio of the total field (E_r) of the CED to the normal field (E_n) (right) for the presented model (left). 1000_bottom, CED on the bottom of the 1000-m deep sea; 100_bottom, CED on the bottom of the 100-m deep sea; 1000_top, CED on the sea surface (1000 m); 100_top, CED on the sea surface (100 m).

CED is optimal and virtually uncontested (Mogilatov and Zlobinskii, 2016). The experience of self-propelled platform (SP) stations shows that, during the drift, the station passes a long path in the Arctic regions in which information about the geology of the bottom is extremely scarce. The current plan is to organize new drifting stations on the basis of an ice-resistant self-propelled platform (ISP), which gives a new reality the project of geophysical research in the Arctic, including electromagnetic sounding (Fig. 2).

The technology of sounding with a CED from the surface of an ice floe is justified and developed in this paper, and the main goal here is to create operational mathematical software of a three-dimensional nature.

TRANSIENT OF THE CED IN A ONE-DIMENSIONAL MEDIUM

Thus, in contrast to ABMN used in CSEM, a CED allows one to place all elements of the receiving and feeding configuration and perform all measurements on the sea surface. However, the frequency mode requires great rafting to compensate for the normal field. It is possible to eliminate this disadvantage using a transitional mode. As already mentioned in Introduction, the transient mode allows one to suppress a background one-dimensional signal and identify an anomalous signal without using great rafting, which may be carried out from the sea surface. We consider the transient in the same medium that is used above (Fig. 1) for the frequency mode. Here, the CED radius is 1414 m, the current is 1000 A, and the rafting is only 2000 m. Figure 3 shows the anomalous effect curves in a time range for the CED and measurements on the sea surface and on the bottom, for deep (1000 m) and shallow (100 m) seas. In all cases, there is an excellent anomalous effect in a measurable signal range. The estimate of external noise in the electric field components is given in (Constable, 2010; Flekkøy et al., 2012). The vertical arrow indicates the time at which the responses per unit of the CED moment reach a threshold noise of 1E-15 V/(A·m^2), determined in the above-mentioned work. Thus, the source

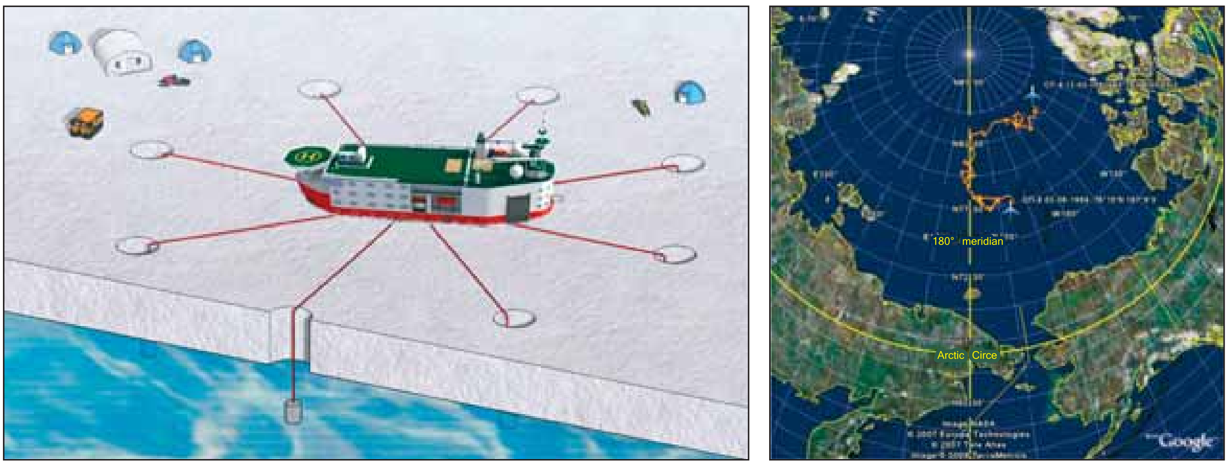

Fig. 2. General view of the electrical power unit on the Arctic ice with the use of an ISP and the possible field of study (SP-8 station drift).

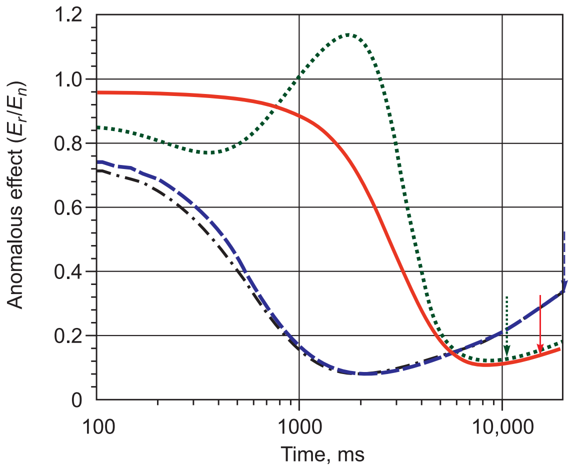

Fig. 3. Total field (E_r) of the CED versus the normal field (E_n). See denotations in Fig. 1. Vertical arrows denote the time at which signals fall below the level of possible measurements.

in the form of a CED in a transition mode allows for eliminating the influence of the surrounding medium in the case of placing the entire device on the surface in shallow and deep sea when using the small rafting.

3D MODELING OF THE PULSED FIELD OF A CED IN THE BORN APPROXIMATION

As shown above, one can easily verify the effectiveness of a CED in the case of a one-dimensional medium. The corresponding mathematical software is available in existing versions and can easily be recreated because the one-dimensional direct problem in geoelectrics is profoundly mastered from a computational standpoint. However, modern research is considered as insufficient with no analysis of the three-dimensional situation. Of course, a three-dimensional modeling means has previously been used. In the transient mode, these are complex and resource-intensive programs used according to the finite element method, which require author support, especially in nonstandard conditions. Of course, if the project is implemented and the required funding is available, such programs are applied to verify the results of interpretation and in-depth modeling. However, flexible operational procedures allowing one to model and also outline the contours of an interpretive technology are already required to justify the proposed methodology with “a drifting CED”. Such a procedure can be constructed on the basis of the perturbation theory, which has been widely used in physics in various fields and has gained the greatest popularity in the form of the Born approximation, which linearizes the direct problem with respect to a small three-dimensional perturbation in a one-dimensional medium. It is linearization that yields the prospect of three-dimensional inversion based on the transformation of linear systems that bind the data with the linearized representation of the direct problem. In geophysics, this approach is also widely used and sufficiently described, for example, in (Zhdanov, 2007). In geoelectromagnetic practical aspects, such an approach has long been proposed in (Mogilatov and Epov, 2000). However, the Born approximation has previously been quite successfully implemented in inductive electrical prospecting problems in which the TE polarization field prevails. The CED field has TM polarization and, accordingly, a vertical electric component. Therefore, the Born approximation works worse here because it does not take into account boundary condition perturbations. Nevertheless, below it is attempted to construct a similar algorithm for a CED field in the transient mode.

Thus, the source is a CED with current I and radius a, whose center is at point $S(x_0, y_0)$ on a day surface (for uncertainty). The harmonic mode is considered first. A normal (one-dimensional) solution is known:

$$E^0_{x,y,z}(x,y,z,S,\omega) = I \cdot e^0_{x,y,z}(x,y,z,S,\omega). \quad (1)$$

Let there be conductivity perturbation $\Delta\sigma$ in region $V(\bar{x},\bar{y},\bar{z})$. In this region, the first Maxwell equation is

$$\text{rot}\,\mathbf{H} = \sigma_0 \cdot \mathbf{E} + \Delta\sigma \cdot \mathbf{E}, \quad (2)$$

where σ_0 is the 1D medium. Let $\Delta\sigma \cdot \mathbf{E}$ be considered as an additional source in the 1D medium. The perturbation region can be represented by a set of electrical dipoles with moments $dI_{x,y,z} = \Delta\sigma \cdot E^0_{x,y,z} \cdot d\bar{x}d\bar{y}d\bar{z}$, where $E^0_{x,y,z}$ denotes the electrical components of the normal (unperturbed) field that replaces the total field. It is the replacement of the total field by the normal field that yields an approximate linearized solution. Figure 4 shows this scheme for generating the anomalous conductivity perturbation response $\Delta\sigma$ in the rectangular region V.

Thus, assuming that perturbation $\Delta\sigma$ in region V generally has a weak impact on the total transient, we should account for all secondary horizontal and vertical dipoles at an

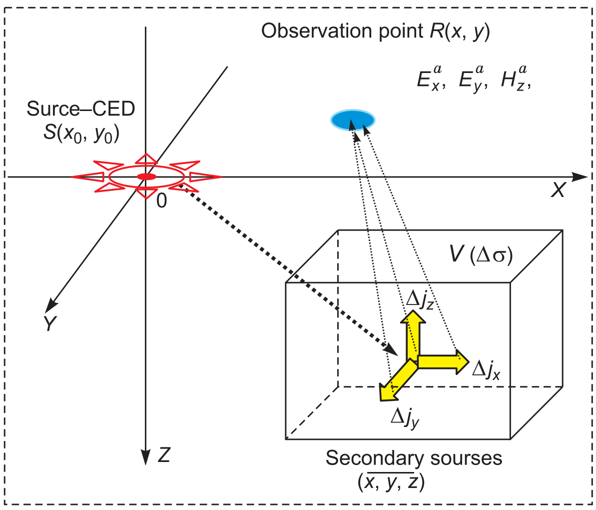

Fig. 4. Generation of an anomalous response by secondary currents.

observation point $R(x, y)$ on the day surface, i.e., calculate all terms of the form

$$I \cdot \Delta\sigma \cdot \iiint_V e^0_{x,y,z}(\bar{x},\bar{y},\bar{z},S,\omega)e_{x,y,z}(R,\bar{x},\bar{y},\bar{z},\omega)d\bar{x}d\bar{y}d\bar{z}\ . \quad (3)$$

As an example, we describe only the contribution of the vertical field of the CED into the anomalous part of component E_x, i.e.,

$$E^a_x = I \cdot \Delta\sigma \cdot \iiint_V e^0_z(\bar{x},\bar{y},\bar{z},S,\omega)e_z(R,\bar{x},\bar{y},\bar{z},\omega)d\bar{x}d\bar{y}d\bar{z}\ , \quad (4)$$

for which the CED field in the medium and the vertical electric dipole field should be known. The vertical electric component of the CED has the form (Mogilatov, 2014)

$$E_z(r,z,\omega) = -\frac{I}{4\pi}\int_0^\infty J_0(\lambda r)\left[1-J_0(\lambda a)\right]\lambda V(z,\lambda,\omega)d\lambda, \quad (5)$$

where the function is the solution of the corresponding boundary-value problem and satisfies the equation

$$V''_{zz} - u_i^2 V = 0 \quad (6)$$

and $u_i = \sqrt{\lambda^2 + k_i^2}$, $k_i^2 = -\mathbf{i}\omega\mu_0\sigma_i$, $i = 0, 1,..., N$ denote the layer numbers. The vertical electric dipole field with moment Idz, in its turn, is (positioned at the origin)

$$E_r(r,z,\omega) = -\frac{Idz}{4\pi}\int_0^\infty J_1(\lambda r)\lambda Z(z,t,\lambda)d\lambda, \quad (7)$$

where function Z also satisfies Eq. (6) (Wait, 1982).

Now, instead of Eq. (4), the anomalous field has the form

$$E^a_x(R,S,\omega) = I\Delta\sigma\frac{1}{(4\pi)^2}\int_0^\infty\int_0^\infty T(\lambda,\lambda')\lambda\lambda' Y(\lambda,\lambda',\omega)d\lambda' d\lambda, \quad (8)$$

where

$$Y(\lambda,\lambda',\omega) = \int_{z_1}^{z_2} V(\lambda,\omega,\bar{z})Z(\lambda',\omega,\bar{z})d\bar{z} = \left[\frac{V'_z(\lambda)Z(\lambda') - X(\lambda)Z'_z(\lambda')}{\lambda^2 - \lambda'^2}\right]\Bigg|_{z_1}^{z_2},$$

$$T(\lambda,\lambda') = \left[1 - J_0(\lambda a)\right] \cdot \int_{x_1}^{x_2}\int_{y_1}^{y_2} \phi(S,R,\bar{x},\bar{y})J_1(\lambda r_1)J_0(\lambda r)d\bar{x}d\bar{y},$$

$$r_1 = \sqrt{(\bar{x}-x_0)^2 + (\bar{y}-y_0)^2},$$
$$r_2 = \sqrt{(x-\bar{x})^2 + (y-\bar{y})^2},$$

x_i, y_i, and z_i are the boundaries of the rectilinear object, and ϕ is the geometric factor that accounts for mutual position of the source, the receiver, and the object (angular coefficient).

We should also consider Y for $\lambda = \lambda'$. In a time domain, the solution is obtained by converting the Fourier transform (8)

$$F(x,y,z,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{1}{-\mathbf{i}\omega}f(x,y,z,\omega)e^{-\mathrm{i}\omega t}d\omega. \quad (9)$$

This algorithm is implemented on software. When codes are written (in Fortran), it is taken into account that function (integral) T is frequency-independent and calculated once, and the value matrix $Y(\lambda, \lambda')$ is calculated using the previously determined vectors $V(\lambda)$ and $Z(\lambda)$. In general, it can be stated that an algorithm for calculating the approximate response from a three-dimensional medium is developed with help of the algorithms and the elements of a semi-analytical "one-dimensional" mathematical apparatus. As a result, the 3D_CED procedure for calculating an anomalous signal from a local rectangular object is written and tested.

Testing is carried out using the calculations based on the GeoPrep software (Persova et al., 2011). This software uses the finite element method. 3D_CED and GeoPrep based comparative calculations are performed for the following conditions (Fig. 5):

1) 3D medium: ρ = 0.3, 2, 1000 Om·m and d = 2000, 3000 m;

2) object: ρ = 100 Om·m, a size of 2000×4000×100 m, and its bed is located at a depth of 4000 m;

3) CED: a radius of 5000 m, a current of 1000 A, and its location is on the medium (sea) surface, at the origin;

4) observations: E_r and dB_z/dt at 441 points with a step of 500 m on the surface.

Figure 6 shows the comparison of the 3D_CED and GeoPrep based calculations of dB_z/dt (more accurately, the EMF from the inductive receiver equal to 10^6 m^2). The calculations are presented in the form of areal images of the signal at a fixed transient time (20.9 s). Inhomogeneity (denoted by a rectangle in the plan) is quite noted by anomalies of different polarity. There is good qualitative and quantitative correspondence. Nevertheless, this result should not be overestimated as the calculation is given for the anomalous (which is also total) magnetic field, formed due to horizontal cur-

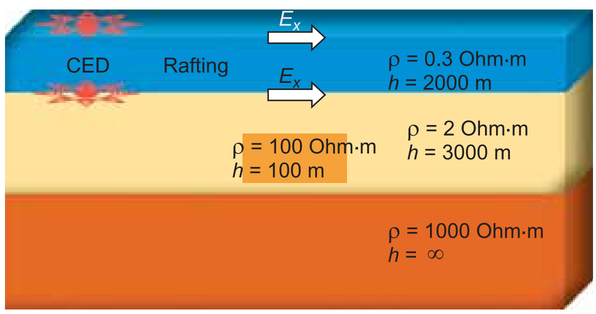

Fig. 5. Model of the medium for performing the 3D_CED and GeoPrep based calculations.

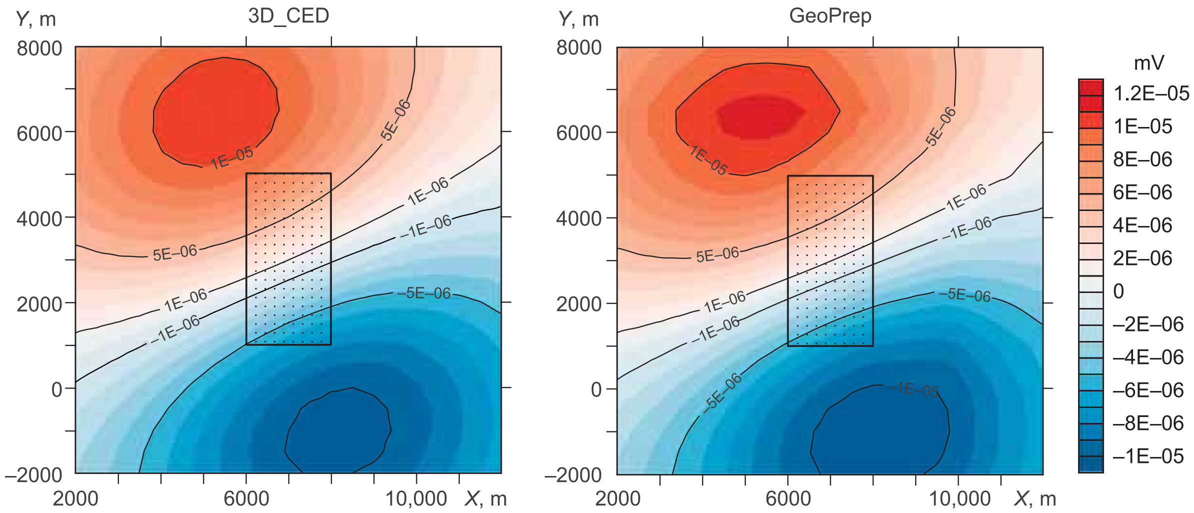

Fig. 6. Comparison of the 3D_CED and GeoPrep based calculations of the signals in the form of the map of EMF isolines at an instance $t = 20.9$ s.

rents (TE field), and it means that there are better conditions for the Born approximation. It should also be noted that, despite the very large moment of the sensor (but such is still possible), the signal is very weak.

The comparison of the anomalous electric fields is more informative. Figure 7 gives such a comparison (more precisely, the EMF with a receiving line radial of 2000 m). From a geophysical point of view, the result is quite satisfactory. Finally, the transient curves are compared (dB_z/dt and E_r denote the total and anomalous fields, respectively) in Fig. 8. According to the principles of the (low-frequency) Born approximation, the curves match better at later times.

Here the matching is discussed with account for the conventionality of comparing the exact and approximate approaches. However, the finite element calculation has its problems at early times. On the whole, the comparison shows that the Born approximation is efficient during the transient when calculating the anomalous field of the CED. The model described in this study and being quite relevant for simulating soundings in the Arctic from the sea surface and for

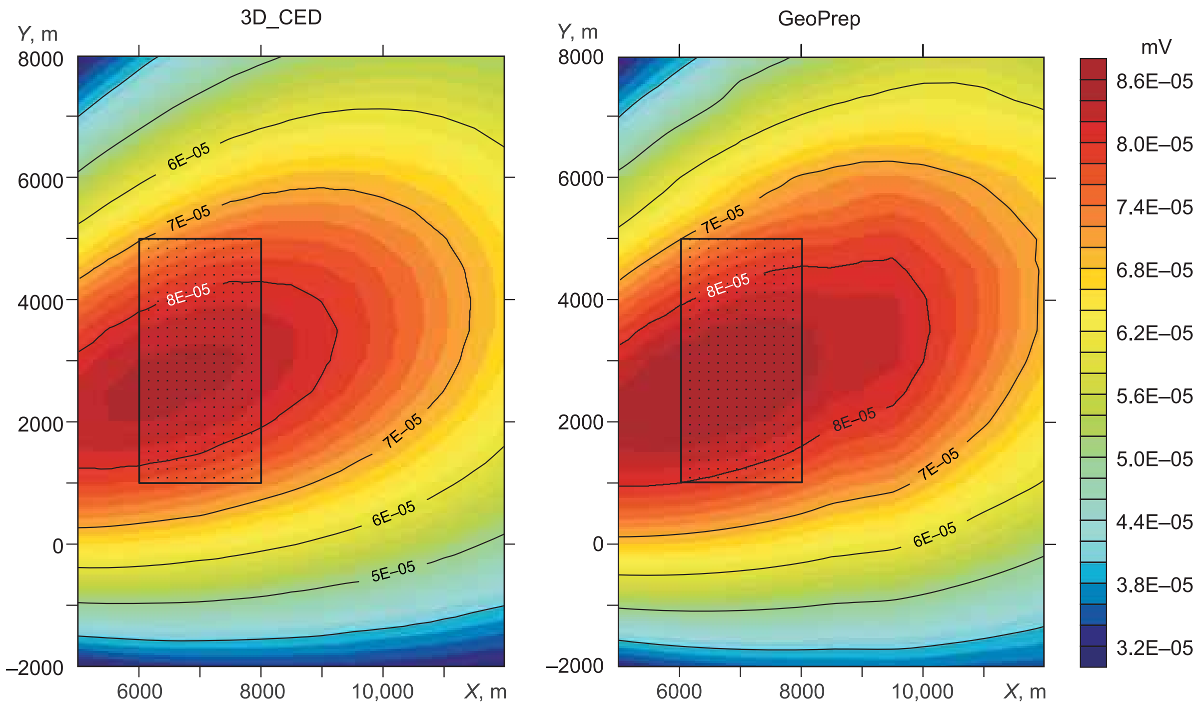

Fig. 7. Comparison of the 3D_CED and GeoPrep based calculations for the anomalous field (E_r) at an instance $t = 27.3$ s.

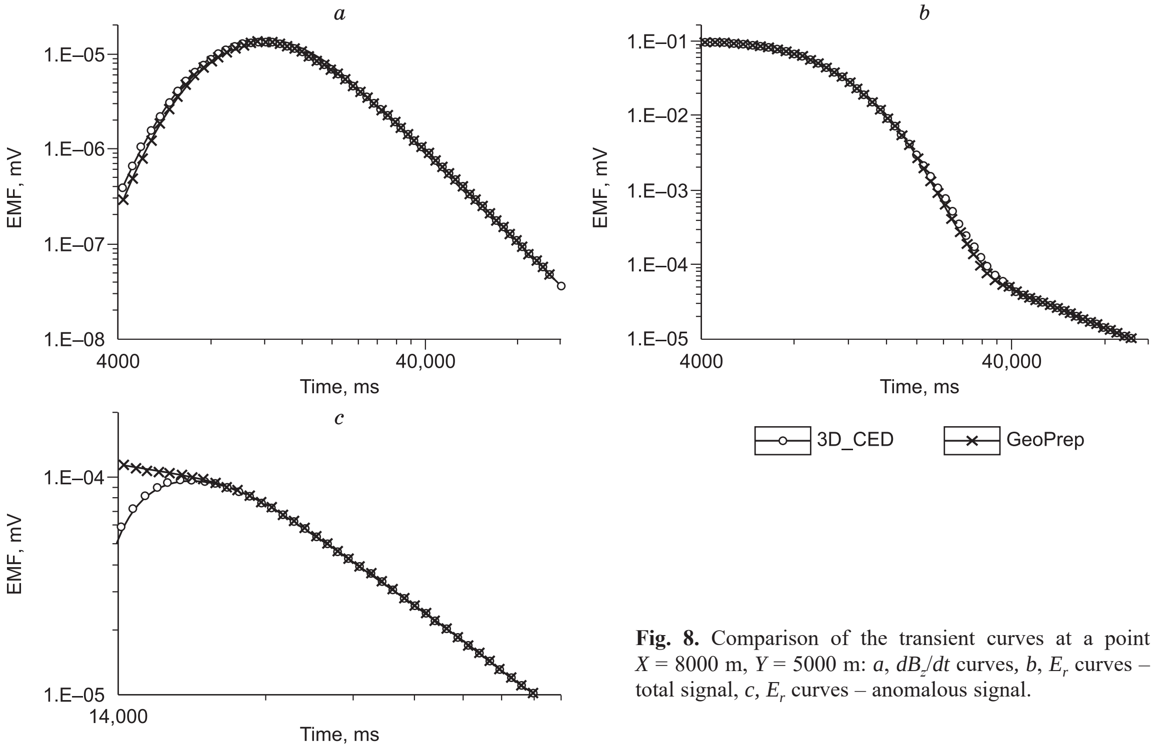

Fig. 8. Comparison of the transient curves at a point X = 8000 m, Y = 5000 m: *a*, dB_z/dt curves, *b*, E_r curves – total signal, *c*, E_r curves – anomalous signal.

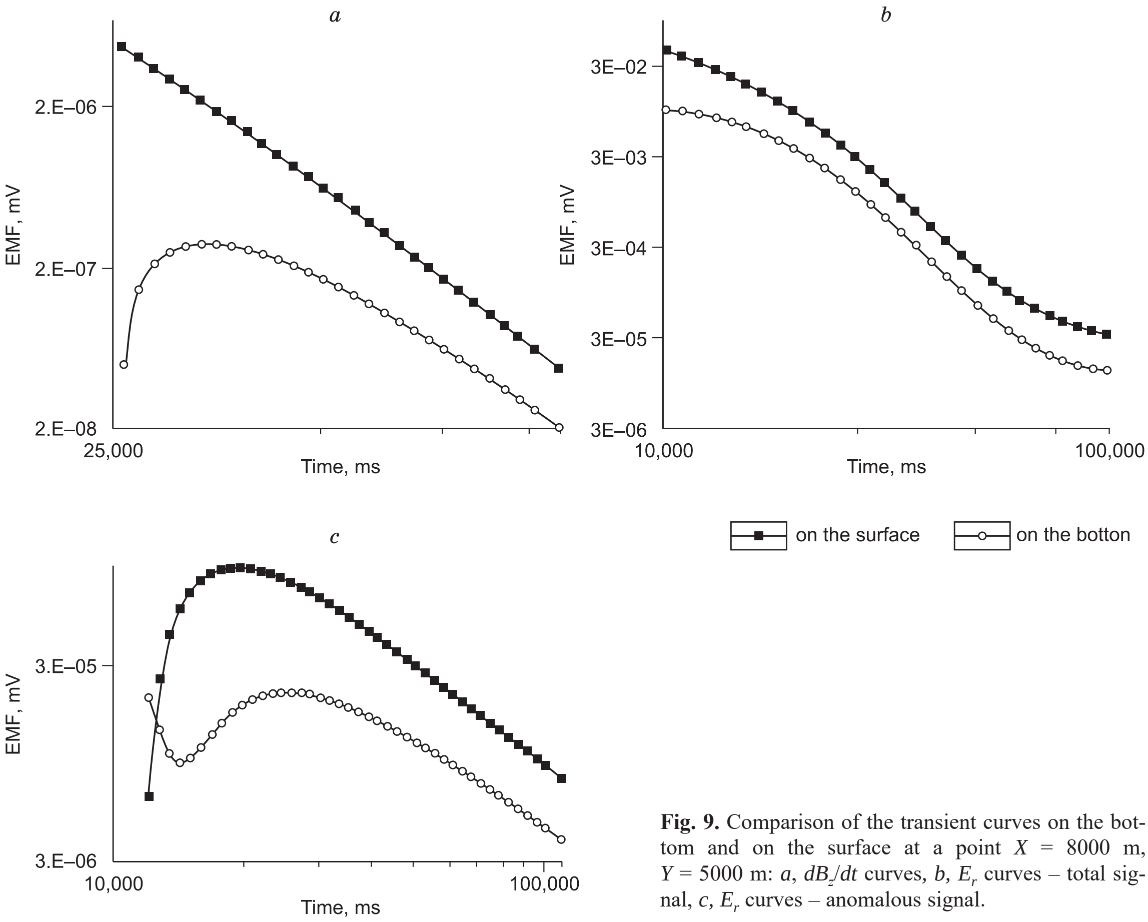

Fig. 9. Comparison of the transient curves on the bottom and on the surface at a point X = 8000 m, Y = 5000 m: *a*, dB_z/dt curves, *b*, E_r curves – total signal, *c*, E_r curves – anomalous signal.

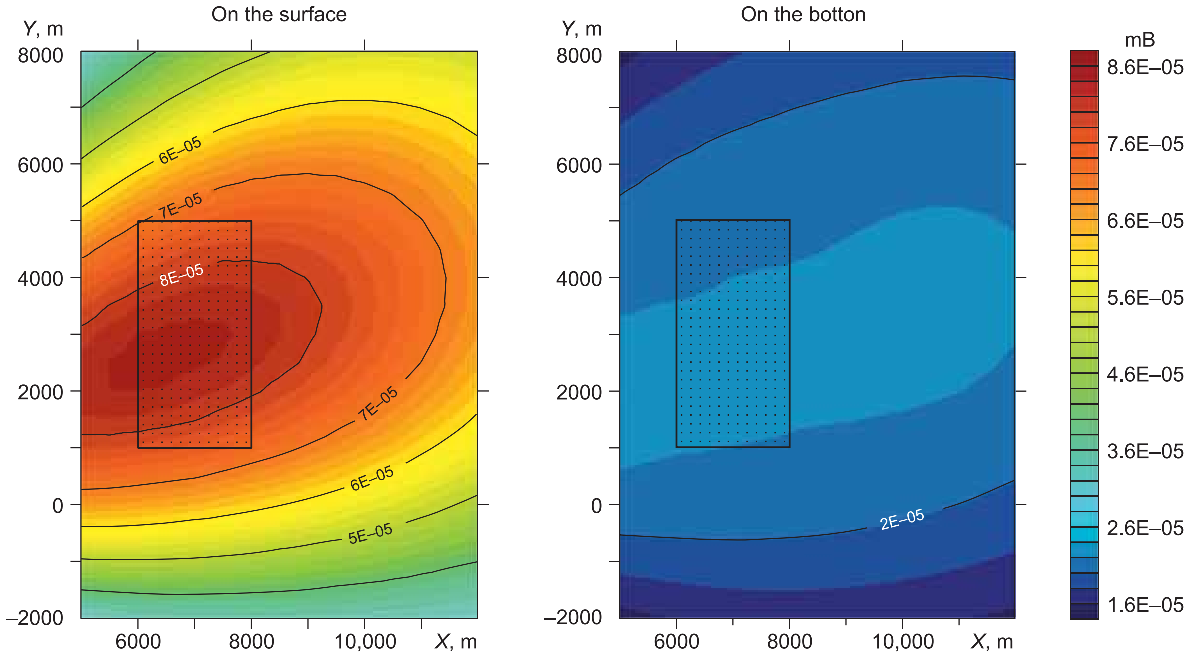

Fig. 10. Anomalous electric field E_r in the case of placement on the surface and on the bottom at an instance t = 27.3 s.

detecting inhomogeneities at great depths is, of course, favorable for the Born approximation. Thus, we can continue the analysis using the approximate algorithm.

COMPARING THE FIELDS OF THE SUBMERGED CED AND THOSE ON THE SURFACE

In marine electrical exploration, there is an established opinion that a device should be submerged, bringing it closer to the object of study. Of course, this is very reasonable and understandable from a physical point of view. However, for the proposed method of sounding from drift ice, a bottomed device is completely unacceptable. It is necessary to show that the receiving and feeding unit with a CED is not less efficient when located on a sea surface (on ice). Actually, it has already been established that the losses are very low in sounding a one-dimensional medium from a sea surface (using a CED, of course). But what happens if the object is local? Let 3D_CED be used to compare the anomalous effect with the submerged device and the surface one.

In Figure 9 where the transient curves are shown, it can be seen that the signals from the bottomed installation are more complex. This is a manifestation of a more complex transient of the submerged CED. The fact is that the field of the submerged CED is quadrupole. The response is formed

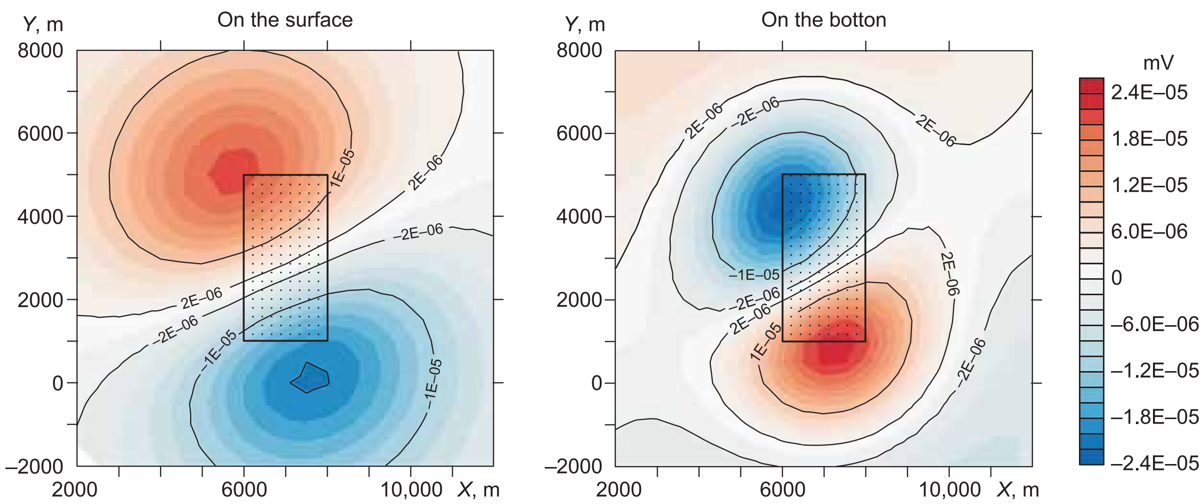

Fig. 11. Comparison of B_z/dt on the surface and on the bottom.

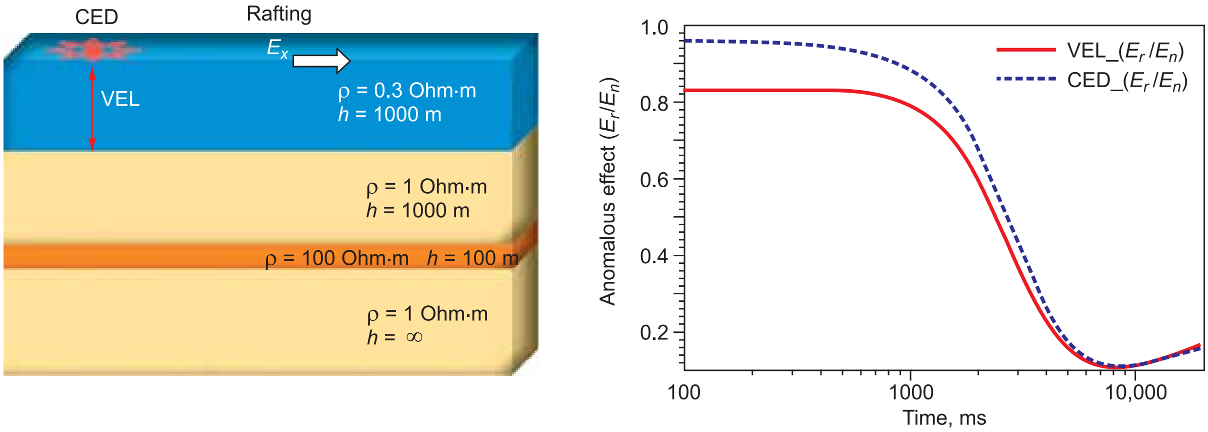

Fig. 12. Comparison of the VEL and CED fields in the form of anomalous effects from a high-resistivity layer. The CED radius is 1441 m, and the rafting is 2000 m.

as a result of interaction between two toroidal current systems – under the CED and above the CED in the sea layer. This issue is discussed in (Mogilatov et al., 2017). Meanwhile, it follows from Figs. 9 and 10 that the signal level, at least, does not fall on the surface. Let us also compare magnetic measurements (dB_z/dt) in Fig. 11. The patterns are completely different qualitatively, but the signal level is the same.

In fact, an important, albeit somewhat paradoxical result is obtained: the immersion of the CED only harms the efficiency of this source. Therefore, there is every reason to place the device on a sea surface without any regrets, which is quite suitable in the context of soundings from continuously drifting ice.

VERTICAL ELECTRIC LINE

Persistently suggesting a CED as a power supply for a device on drift ice, we should also consider a simpler source in the form of a vertical electric line (VEL). It is known that a CED is an analogue of a VEL, and both are the TM polarization field sources, which ensures highly efficient soundings. This analogy even provides a quantitative match with fulfillment of a certain ratio between the moments. This is shown in Fig. 12.

The use of a VEL in the sea is considered and studied. For example, there is a thorough study (Barsukov and Fainberg, 2016). PetroMarker AS (Norway) has practical experience working with such a source. Nevertheless, we consider a VEL to be an inappropriate source. Firstly, it is subject to slopes and vibrations, which is very critical for the TM field quality. Figure 13 shows the modeling results of the transient of a “virtually” vertical line when measured by a “virtually” vertical line (the lengths of the feeding and receiving lines are 1000 and 600 m, respectively, and the rafting is 100 m). Calculations are carried out using rather nontrivial (albeit one-dimensional) ELinc2, developed by us and allowing for calculating arbitrary inclined lines in layered media. So, even small inclinations (here 2°) lead to a qualitative change in the response, including a change in sign.

The second obvious drawback is that the length of a VEL depends on the sea depth. During drift, the sea depth can vary significantly from a few hundred meters to 4000 m. A powerful source is needed, but the length of a VEL may be insufficient. Nevertheless, when designing an electromagnetic ex-

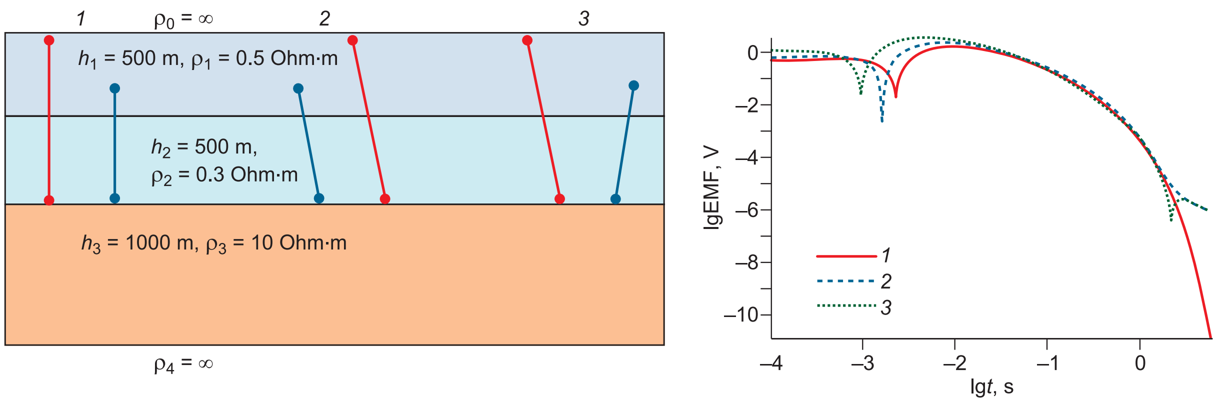

Fig. 13. Impact of slopes. Model of the medium, the three situations (*1–3*), and the EMF curves.

periment on drift ice, one should have a VEL "in stock" in the case of disintegration of ice fields and damage to the CED.

CONCLUSIONS

Certainly, this study ignores many other important and practical problems pertaining to the application of a large-scale CED on ice. First of all, one should study the effect of induced polarization processes on signals from such a purely galvanic device and the stability of the device geometry in the case where the device is mounted on drift ice. Nevertheless, in principle, the use of a CED solves the main problem of marine electrical exploration – the shielding effect of a sea water layer and even in the case of sounding from the sea surface. This makes it possible to suggest a CED as a source on drift ice. The transient sounding method in this format can take its rightful place in the geophysical complex within the framework of the proposed experiment on studying the geology of the bottom of the Arctic basin under conditions when traditional geophysical methods cannot be applied. Although this does not pertain to the essence of this study, it is possible to point out yet another application of a CED – as a receiving device for recording in magnetotelluric soundings, which allows recording the vertical component of a magnetotelluric field at great depths. This is a serious innovation and a significant addition to the electromagnetic component of the geophysical experiment on drift ice in the Arctic.

This work was financially supported by the Russian Science Foundation, grant No. 18-17-00095.

REFERENCES

Barsukov, P.O., Fainberg, E.B., 2017. Marine transient electromagnetic sounding of deep buried hydrocarbon reservoirs: principles, methodologies and limitations. Geophys. Prospect. 65 (3), 840–858.

Constable, S., 2010. Ten years of marine CSEM for hydrocarbon exploration. Geophysics 75 (5), 75A67–75A81.

Constable, S., Srnka, L.J., 2007. An introduction to marine controlled-source electromagnetic methods for hydrocarbon exploration. Geophysics 72 (2), WA3–WA12.

Flekkøy, E., Haland, E., Maløy, K., 2012. Comparison of the low-frequency variations of the vertical and horizontal components of the electric background field at the sea bottom. Geophysics 77, E391–E396.

Goldman, M., Mogilatov, V., Levi, E., Tezkan, B., Haroon, A., 2015. Signal detectability of marine electromagnetic methods in the exploration of resistive targets. Geophys. Prospect. 63 (1), 192–210.

Mogilatov, V.S., 2014. Pulsed Geoelectrics [in Russian]. Izd. NGU, Novosibirsk.

Mogilatov, V.S., Epov, M.I., 2000. Tomographic approach to the interpretation of geoelectromagnetic sounding data. Izv. Phys. Solid Earth 36 (1), 70–77.

Mogilatov, V.S., Zlobinskii, A.V., 2016. Geoelectric experiment in the Arctic (Project). Geofizika, No. 1, 75–80.

Mogilatov, V.S., Zlobinsky, A.V., Balashov, B.P., 2017. Transient electromagnetic surveys with unimodal transverse magnetic field: ideas and result. Geophys. Prospect. 65 (5), 1380–1397.

Persova, M.G., Soloveichik, Yu.G., Trigubovich, G.M., 2011. Computer simulation of geoelectromagnetic fields in three-dimensional fields by the finite-element method. Izv. Phys. Solid Earth 47, 79–89.

Wait, J.R., 1982. Geo-Electromagnetism. Academic Press, New York.

Zhdanov, M.S., 2007. Geophysical Inverse Theory and Regularization Problems. Elsevier Science B.V., Amsterdam, The Netherlands.

Editorial responsibility: I.N. Yeltsov