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Influences of the Earth's Magnetic Field on the Transient Electromagnetic Process in the Geoelectric Field: an Experimental Study

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Abstract—A mathematical model of the influence of the Earth's magnetic field (the Hall effect) on results of the controlled source transient electromagnetic (TEM) method has been elaborated. For identification of this effect, we propose a schematic layout of the experimental grounded system with a pulsed loop source and signals recording by radial receive lines equally spaced relative to the loop. The 2018–2019 special field experiments were conducted in the Tatar region of the West Siberian Lowland with an aim to estimate the Hall effect contributions to the TEM method. To detect the Hall effect, transient electromagnetic responses were measured mainly by four receive lines radiating from a 500×500 m square loop. Analysis of the TEM results processing aimed at improving the signal quality and reducing the interference revealed a great similarity in signals from the radial lines, which is theoretically possible only under the Hall effect. Comparison of the field signals with the theoretical ones enabled estimation of the components caused by the Hall effect, in particular, conductivity at ~0.002 S/m.

Keywords: electrical prospecting; controlled source transient electromagnetic (TEM) method; geomagnetic field; Hall effect

INTRODUCTION

The interaction between currents induced in geoelectromagnetic fields and the Earth's magnetic field is in principle based on the Lorentz effect. The Lorentz force manifests itself through the effect of external magnetic field (eddy currents) on moving charged particles and, hence, on the electric current. This force is directed perpendicular to the magnetic field vector and to the direction of the motion of electrically charged particles through it (i.e., to the electric current). This physical phenomenon is remarkably real. The electric current is enclosed within a linear conductor (i.e., a wire carrying a current), while the Lorentz force is transmitted onto the body of a conductor (this actually is what operates spin cycles in our washing machines). In the case of an essentially dimensional conductor ("conducting bar"), an electromotive force (EMF) is produced in a direction that is perpendicular to the direction of the external magnetic field and to the direction of the electric current. Here we deal with the Hall effect – the creation of a voltage (known as the Hall EMF) across a current-carrying conductor by a magnetic field. Ultimately, when a continuum acts as a conductor (a conducting geological medium), a transverse EMF is also induced by any varying currents (natural or artificial), while an external magnetic field (i.e., the Earth's magnetic field) is always present in our environment.

The biggest challenge is to identify real manifestations of this factor in electromagnetic soundings. An elementary analysis suggests that this can show up as effective anisotropy in the conductive earth caused by the Lorentz force and the Hall effect (i.e., Hall's anisotropy of the resistivity). The effect should be very weak in all signals, judging from the fact that it has yet neither been detected nor discussed (except our own assumptions about its possible manifestations in electrical prospecting (Mogilatov, 2013)). In our opinion, the controlled source transient electromagnetic (TEM) sounding measuring magnetic responses ranking as the most sensitive method among geoelectric technologies provides the most appropriate experimental basis for estimating the influence of the geomagnetic field on signals.

Let us consider a simple case of the TEM process of a horizontal current loop (transmitter) in horizontally layered earth. Assume that the Earth's magnetic field is vertical (Fig. 1*a*). Secondary currents are coaxial with the current loop, and an EMF which is induced in this case by the action of the Lorentz force drives current along the radius. Thus, a simple experimental scheme has been proposed (Fig. 1*b*). A pulsed source is represented by a current loop located at the selected site with a planar surface and horizontally layered section (as far as is known). Four radial *MN* lines with

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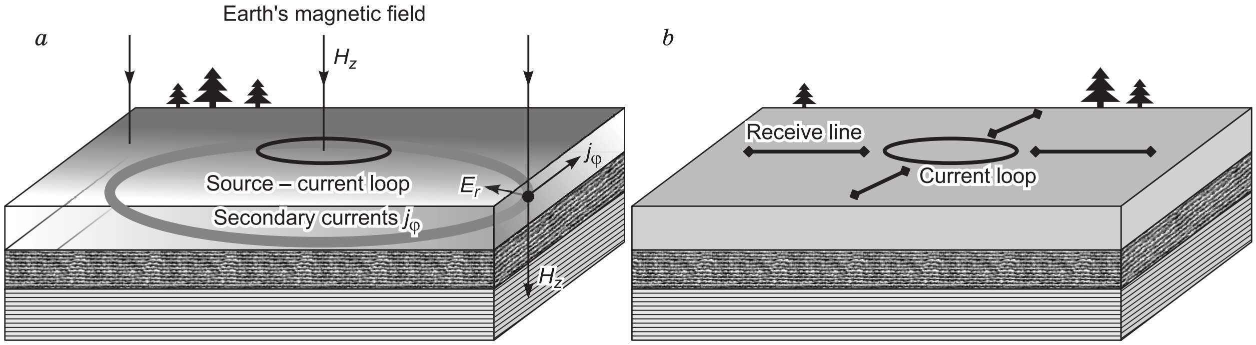

Fig. 1. The Hall voltage (E_r) appearing in the electric field (*a*) and the experimental array for its detection (*b*).

equal positions relative to the loop were used for registration of additional, "Hall" components (i.e., caused by the Hall effect). At this, the measurement lines at this position are remarkable by the absence of normal transient electromagnetic signal, as well as by the induced (IP) polarization signal.

Although the idea appears simple, an expert will easily recognize in the proposed scheme a method for pure anomaly detection, which is always fraught with underlying potential problems. Any distortion of the array system geometry or horizontal uniformity of the cross-section will result in fairly strong signals, which may exceed the wanted ones. We can assure our readers that we had this problem in mind when conducting the field experiments, and this will be discussed below. However, let us mention straightway a crucial criterion that will help determine the nature of signals. The wanted signals associated with the Earth's magnetic field should be identical by virtue of symmetry in all four lines, while all conceivable distortions will yield completely different signals in the four multidirectional receive lines. Although this appears obvious, we will for good measure demonstrate it using 3D mathematical modeling.

Also worth noting is that we have already had an inopportune experience of publishing the results of our study of the influence of the Earth's magnetic field. Being more speculative in nature rather than scientifically proven, despite including some field data and materials, the paper was declined. Whatever emotions were lurking behind, we fully understand that, by claiming to have revealed a new effect in geoelectrics, it is crucial to substantiate our results and findings in the best conclusive and evidential way. With support from the Russian Foundation for Basic Research, we were able to finally conduct specialized field experiments in the Novosibirsk region during the summer of 2018, and to repeat them in 2019, thereby confirming and complementing the obtained results. Hopefully, by doing so, we have significantly raised the level of our argumentation.

PREPARATION OF THE EXPERIMENT

Work area. Major factors that can distort the wanted signal and whose influence should be minimized include the presence of electromagnetic interference; local geological heterogeneities; horizontally inhomogeneous structure of the medium within the work area; distortion of the transmitter -measuring array system parameters (layout of loops and measuring lines on the ground).

After reconnaissance trips for work area selection, two sites near Tatarsk, Novosibirsk region, in the vicinities of Orlovka village were chosen for experimenting. The locality is characterized by planar relief. According to a priori data obtained during the previous geological and geophysical investigations, the work area is classified as almost identical to a horizontal-layered section. The nearest village is located at a distance of 5 km; there are neither industrial facilities, nor high-voltage power lines nearby. The preliminary analysis has thus proven the preparedness of the required conditions for running the experiment. Besides, during the fieldwork, the horizontal-layered structure of the medium was tested by our electrical prospecting tools.

Array layout. The layout of all measurement lines and a transmitter loop at Site 1 is shown in Fig. 2 (the array system

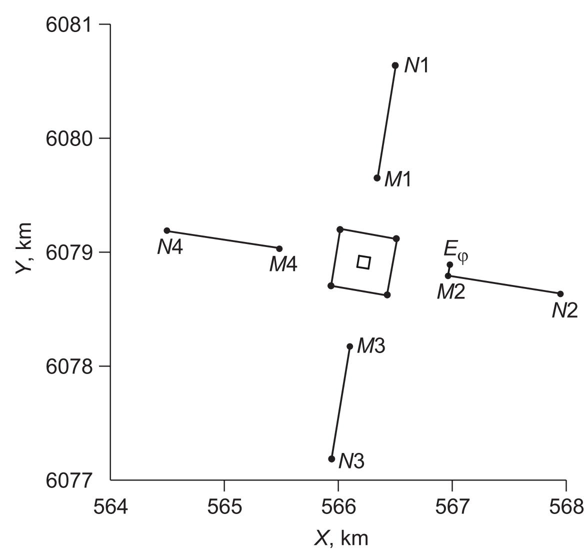

Fig. 2. Experimental array layout at Site 1 with four lines for registration of E_r components and one line for registration of E_φ components. Coordinate systems (WGS84, UTM, zone 43N).

Table 1. 1D geoelectric section derived from the TEM data

No.	R, Ohm·m	Thickness, m
1	10	24
2	7	357
3	4	791
4	15	μ

center: 54.583° N., 76.0314° E.). The transmitter loop (500×500 m, GPMP cable) was laid out on the planar surface. All radial current lines were positioned equally in respect to the loop and were grounded by non-polarizing electrodes at a distance of 750 and 1750 m from the center. With due account of ground conditions, we tried to arrange the loop and measuring lines in the N–S and E–W directions, using a 1 km long telephone steel-copper cable for its grounding.

Equipment. The two types of TEM measurements systems used in the experiments are 1) a Cycle-7 (Novosibirsk), 2) FastSnap (Irkutsk). The transmitter unit included a Cycle-T50 current switch block and switch control (produced by the same manufacturer, Novosibirsk). The measurements were synchronized via GPS. The loop was powered by batteries (11.5–12.5 A).

Auxiliary studies and geological environment. Firstly, coaxial controlled source transient electromagnetic soundings were carried out using a 500×500 m transmitter loop and a 100×100 m receive loop prepared for the main experiment (Fig. 2) The TEM responses were measured with the Cycle-7 and FastSnap systems, which yielded identical results. Thus, a 1D-geoelectric model of the medium presented in Table 1 was derived from the interpretation of coaxial TEM measurements. The main measurements were supposed to be made from the grounded lines. The electrical measurements required testing, though. This can be done by measuring the normal, "ordinary" components of the transient field of the current loop, namely, the E_φ component (Fig. 2). Let us apply the control procedure described below.

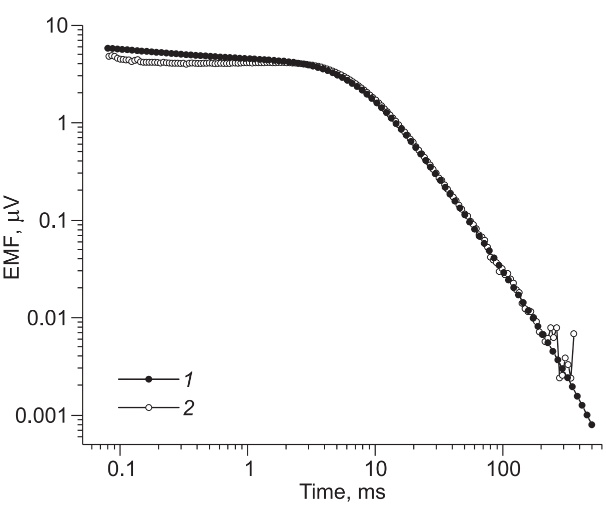

Fig. 3. Comparison of theoretical (*1*) and measured (*2*) transient signal of components E_φ at Site 1.

For the medium obtained as a result of the interpretation of the coaxial transient (TEM) responses (Table 1), we can calculate a signal for a short measuring electric line that is perpendicular to the main line. Now we compare the calculated signal with the real signal measured (Fig. 3). One can observe the signals matching, which is a remarkable result meaning that the adequacy of our electrical measurements (from grounded lines) is confirmed. Moreover, interpretation of the coaxial transient measurements also proved it to be a signal in 1D medium with the parameters as exactly specified above, since we now use signals (measured and theoretical) that are substantially remote from the loop center (offset is 750 m). Early in the experiment, refining the 1D structure of the near-surface section may be required.

THE 2018 FIELD MEASUREMENTS

Figure 4 shows transient responses from all four lines measured in 2018. These appear to be appreciable signals in the context of the implementation of the controlled source transient electromagnetic (TEM) method. The curves show EMF charged by 1 A on the source. Given that the pulsed current reached 12 A, the signals (voltage in the receiver line) at the beginning of the transient process were approximately 1 mV. One of the challenges we faced during the 2018 field works was the unstable and oftentimes nasty weather (storms, thunderstorms, rainstorms), and the situation was exacerbated by our time and financial constraints. Hence, the quality of the measurements was largely nonuniform. We, nevertheless, consider the work result nonnegative. The most important is that the signals from the four lines were identical. Of course, only to a certain extent. To show what we mean by defining them so, we present results of the 3D modeling of signals (Ivanov et al., 2009) registered in these four lines in the presence of heterogeneity (Fig. 5). These signals effectively proved not to be the same! Not only do they differ drastically from our signals, but they also differentiate between themselves, both qualitatively and quantitatively. Since the source of the signals is heterogeneous subsurface with 3D structure, the transient process is started from the zero level.

Understandably, we have performed more extensive modeling based on diverse heterogeneities, and we can confidently ascertain that our field signals are independent of heterogeneity in the cross-section. However, heterogeneity *per se* was not an issue with the study area where the experiment was conducted. This is corroborated by the analysis of the geological and geophysical data archive and our auxiliary measurements.

THE 2019 FIELD MEASUREMENTS AND MAIN RESULTS

Although the results of the 2018 field works were encouraging, they were rather incomplete. It was decided to

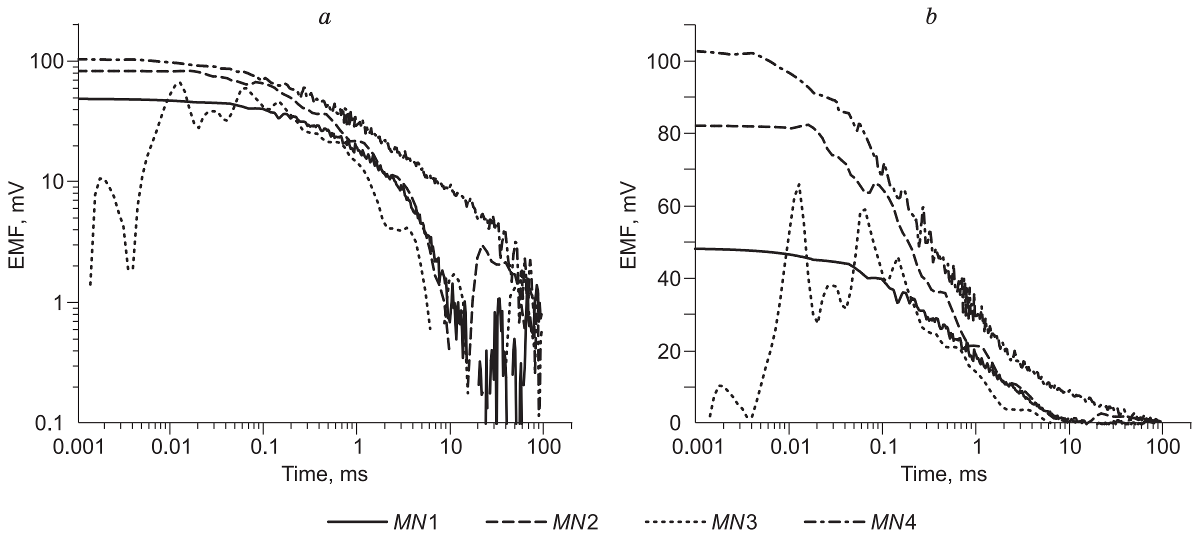

Fig. 4. TEM curves of the field component E_r in four radial lines at Site 1 (2018). On bi-loglogarithmic (*a*) and linear (*b*) scale.

continue the experiments in 2019 within the same study area, in order to analyze signals' repeatability. Given that primarily we were able to substantially widen the scope of field works, the highlights of the 2019 field works are: (i) the previous year's measurements were repeated at exactly the same location using the autonomous data acquisition system layout; (ii) measurements at Site 2 were performed with the whole source-receiver system relocated several kilometers and slightly twisted (the array system center: 54.952° N; 76.114° E); (iii) auxiliary measurements of the

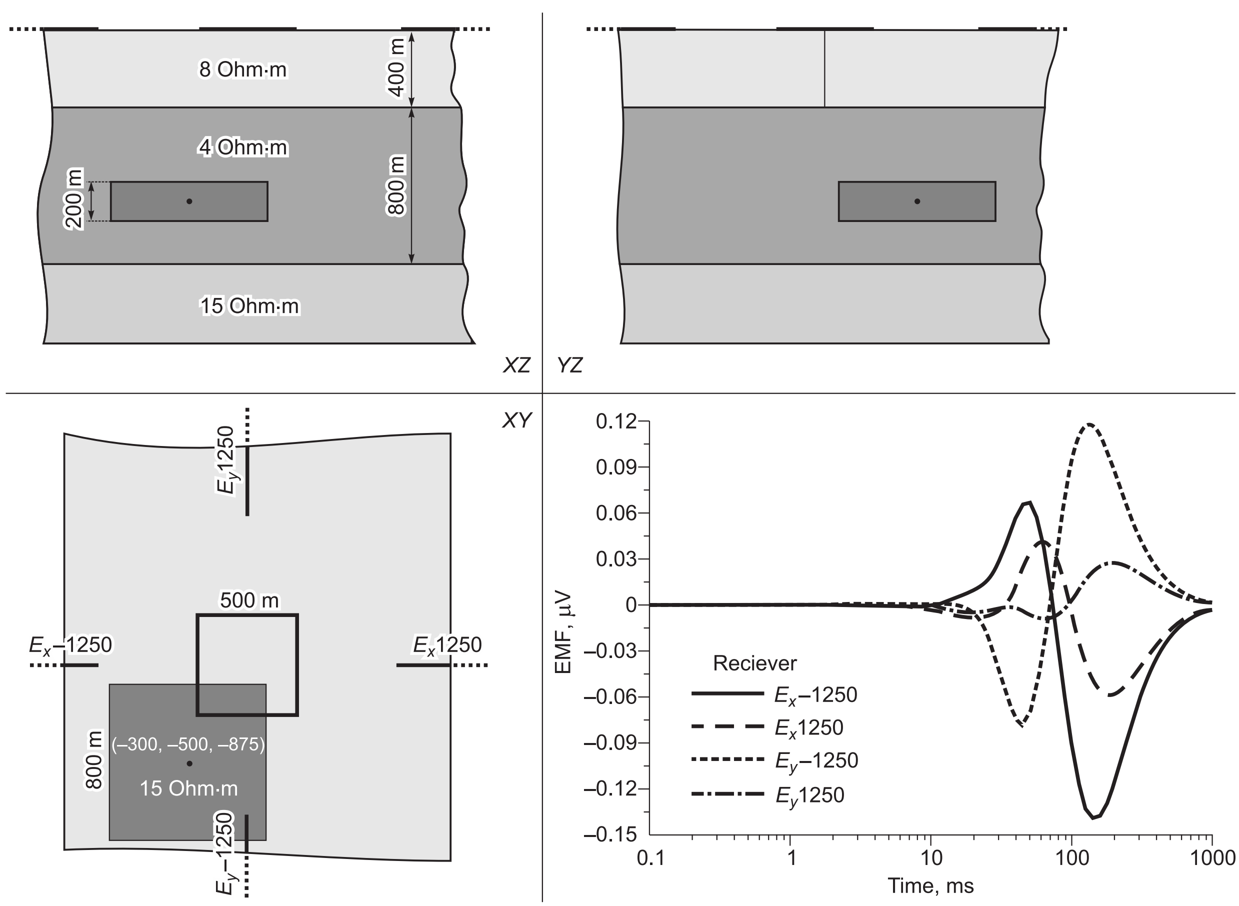

Fig. 5. TEM curves in four radial lines in the presence of local heterogeneity.

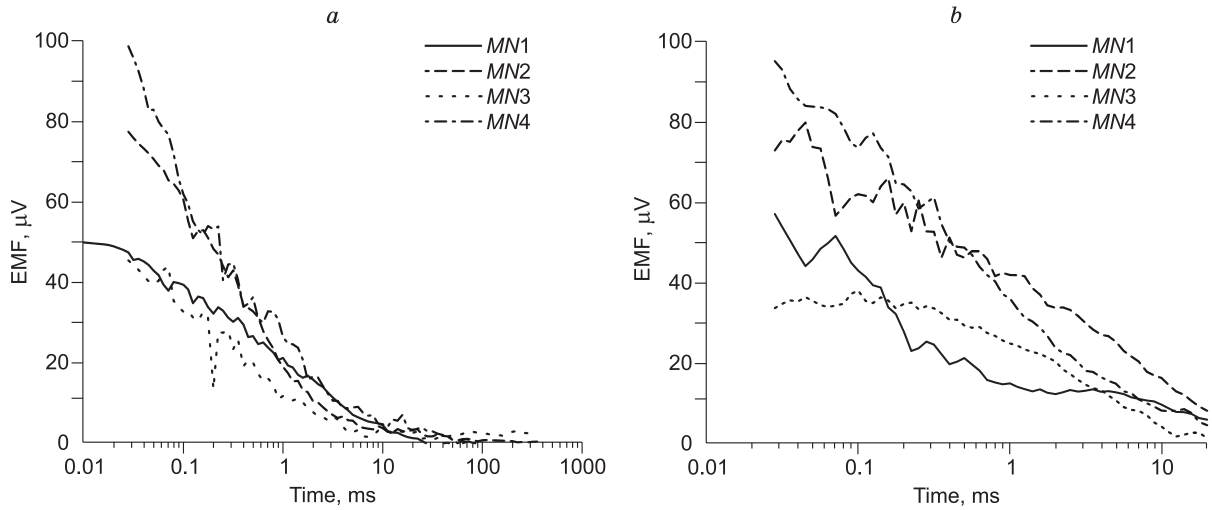

Fig. 6. Comparison of the TEM curves of four *MN* radial lines in 2019: *a*, At Site 1, *b*, at Site 2.

normal tangential component of the transient field (E_φ) near the proximal (inner) ends of all four main radial receive lines were more extensive than in 2018, while shallow-depth TEM soundings were performed at the distal ends of receive lines in order to more thoroughly investigate horizontal homogeneity of the medium.

Now we discuss the main cumulative key outcome, with the 2018 fieldwork results added up. Figure 6 represents new signals from the four receive lines at the first point (where the system layout repeated that of 2018) and signals at the second point. Although the resulting signals have changed to some extent at the second point, it can be acknowledged that they have a stable repetitive behavior and are real.

We demonstrate a comparison of the signals of 2018 and 2019 performed on the bi-logarithmic scale (Fig. 7*a*) and logarithmic scale adopted in the TEM method (Fig. 7*b*).

Thus, signals make difference. Figures 6 and 7 show the values of 1 A source current at a 12 A current in the transmitter loop. Let us elucidate in layman's language on "nuances" of transient responses: TEM signals are always affected by "electromagnetic crosstalk", i.e., interference of other EM signals: natural and industrial, systematic and random, as well as pulsed. During the measurements, the signal was accumulated by virtue of multiple pulse repetition in the medium, and various measures were taken against systematic electromagnetic interference (e.g., measures for industrial interference (50 Hz) protection). Also, signals were duplicated (usually three runs were made). Thus, we find it normal that signals may have a substantially nonsmooth appearance (Figs. 6 and 7), and we can only emphasize that the signals of 2019 and 2018 are largely analogous, while the signals from all four source lines are approximately (with

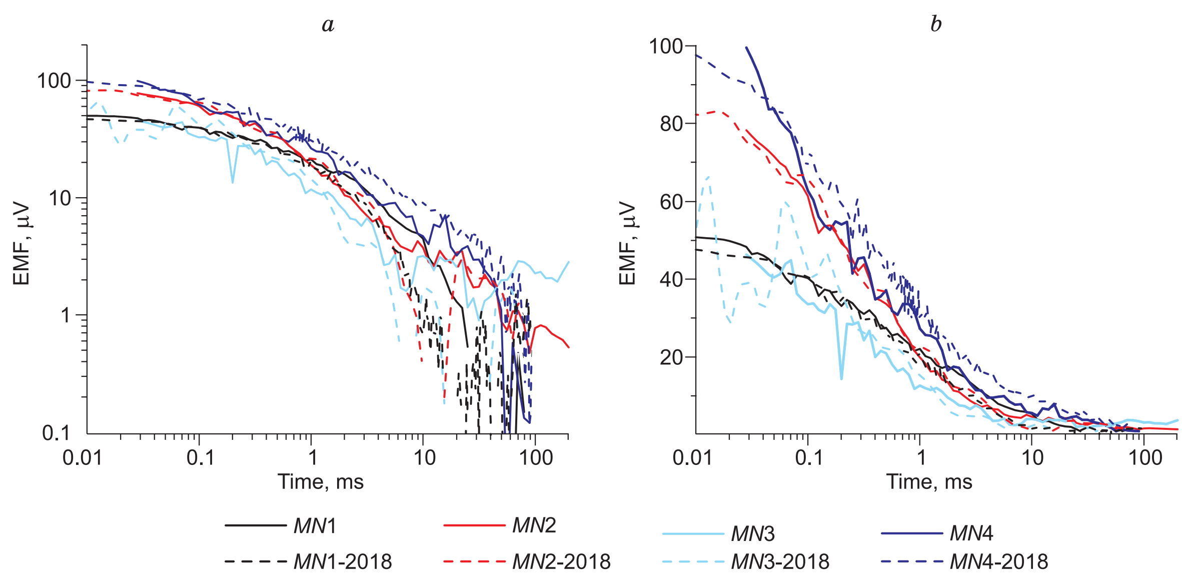

Fig. 7. Comparison of TEM curves of four *MN* radial lines in 2018 and 2019 at Site 1. *a*, Bi-logarithmic scale, *b*, logarithmic scale.

allowance for transient responses) identical. That, in our understanding, is possible if the nature of the signals is interpreted exactly as we suggest.

However, now, proceeding from the totality of all the signals, we can also point out their main difference, by dividing them primarily into two groups according to their sources, which are "latitudinal" (W–E) receive lines (with even indices: 2, 4); and "longitudinal" (N–S) lines (1, 3). In the former group, the signal level is remarkably higher. In terms of signal quality, this can be explained again by the influence of the Earth's magnetic field. Despite that the vertical component has thus far been accounted for alone, note that our geographical latitude is characterized by a significant horizontal component (an inclination of about 70°) (Magnetic field..., 2020), which is about 30% of the magnetic field amplitude. Here, its effect on circular secondary currents generated by the loop is differentiated depending on the geographical orientation of the currents. This horizontal component, which is pointed N–S, does not interact with currents flowing in the same direction while affecting those directed W–E (Fig. 8). Thus, the signals from the "latitudinal" (even) lines should really stand out from the signals of the "longitudinal" (odd) lines. It turns out that a clear distinction between the signals inferred from the geographical criterion is a strong argument in favor of the "Hall" origin of the signals registered by our system.

RESULTS VALIDITY

In the above said, we were concerned primarily with the presentation of our main results and only mentioned the measures taken to ensure proper configuration of the data acquisition system and to analyze potential effects of heterogeneities of the geological medium. Without such measures, the main results would be doubtful. All in all, we have made tremendous efforts towards it in our field works and mathematical modeling.

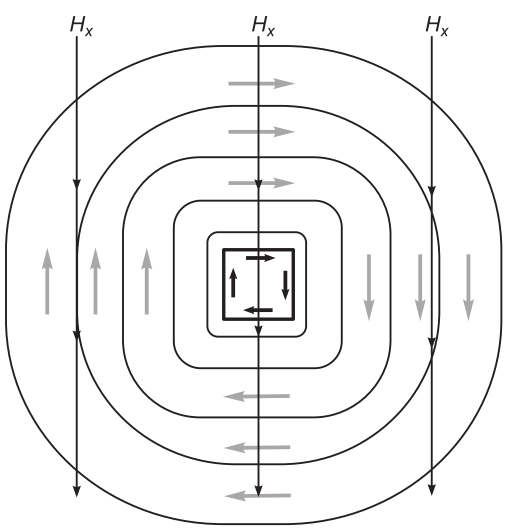

Fig. 8. Source (loop), secondary currents, and horizontal components of the Earth's magnetic field.

The laying of wires was controlled with the Garmin 64st (working with GPS and GLONASS satellites, under specified conditions) for land navigation, thereby ensuring a 1 m positioning accuracy. The work area is well exposed and poorly forested, the simultaneously visible satellites counted at least 10 during the work, which also contributed to the high accuracy of the positioning. In addition to using the navigator, alignment of the loops and *MN* lines was controlled by survey stakes placed to be visible along the wire-laying route, to form a single line. In practical terms, while newly marking and deploying the transmitter loop and *MN* lines in 2019, we found out that some of the stakes mismatched the previous (2018) layout (because of the poorly discernible traces) but with not more than 1 m offset. Thus, the maximum deviation of the source-receiver system from the design layout is no more than 1 m.

We employed mathematical modeling of the transient signals from receive lines with some deviations from the layout within 1 m for the layered medium model derived from the induction measurements (Table 1). Among the results shown in Fig. 9 one can see that the signals are weak (the EMF presented is related to 1 A current) and pose no problem at all for the conditioning data acquisition.

Nevertheless, we've made an impressive amount of measurements during the field works, deliberately introducing deviations from the correct layout scheme. This consisted in moving the grounding points a few meters to the right and left of the prespecified position. Such shifts in the distal grounding points of the receive lines had no effect on the received signal. However, shifts in the proximal ends distorted the signal effectively (Fig. 10*a*). Changes in the signals revealed in all the lines have amounted to the following pattern: the largest positive signal corresponds to a 10 m-offset in the grounding point; with the offset exponentially decreasing, the received signal decreases until its sign changes to negative. This situation proved to be explicit for all eight *MN* lines in 2019 at two points.

Since we also measured the E_φ component near the inner ends of the receive lines using a short (100-m-long) line perpendicular to the main one, we can correct the measurements distorted by the electrode displacement by subtracting the signal corresponding to the offset. Indeed, upon the correction, as shown in Fig.10*b*, we obtain our wanted signal, which can be interpreted as a general basis. In our view, this strongly implies the reliability and completeness of our measurements.

Another major challenge associated with the validity of our anomalous signals is the possibility of generating signals complex by the horizontal inhomogeneity of the medium. We have already shown an example of our 3D modeling (Fig. 5). Its results confirm the viewpoint that any heterogeneity will produce completely different signals in the four

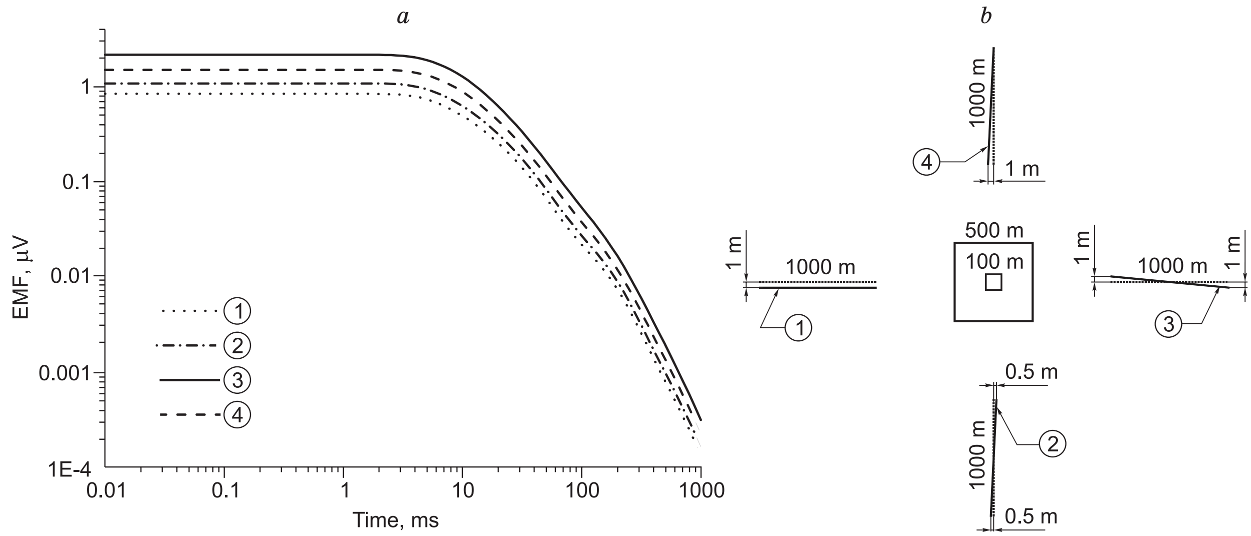

Fig. 9. Modeling of the geometric distortions effects of the array cofiguration: *a*, Signals in *MN* line from distorted configuration, *b*, types of geometric distortion of the array system: 1, 1 m parallell offset, 2, 0.5 m offset in all directions at the ends, 3, 1 m offset in all directions at the ends, 4, 1 m offset at the proximal end.

multidirectional lines, whereas our signals are fairly well repeatable in each line, as they should be (given the previously mentioned).

Moreover, additional measurements taken during the 2019 field studies at the grounding points of the receive lines included: the E_φ component at the proximal ends; coaxial near-surface transient responses at the distal ends. Their results confirmed the absence of any conspicuous heterogeneities capable of producing any profound effect on real data. Instead, only local near-surface inhomogeneities were reported.

Figure 11*a* shows the apparent resistivity curves for large transmitter loops suggesting that the cross-sections representing two points located several kilometers away from each other look very similar. At this, such curves for small (100×100 m) transmitter loops measured at the center and at the distal ends of *MN* lines demonstrate (Fig. 11*b*) that they differ only in the upper part of the section, within the first 200 m.

The E_φ component is very sensitive to the section parameters, while the signals from all lines (both sites of the work area are concerned) differ only for the initial times (Fig. 12). This enabled arrival at the following conclusions: the revealed changes in the section of Site 1 and Site 2 relate only to shallow subsurface, while they are congruent for the section at depths >200 m, and the cross-sections are interpreted as generally matching. This is another proof that the study area largely resembles a 1D section. The differences in the behavior of

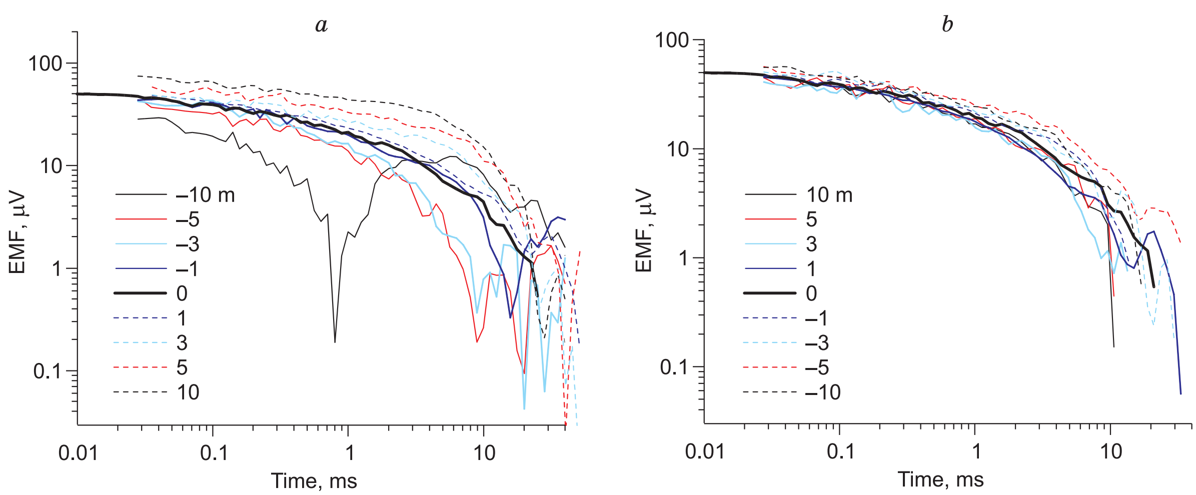

Fig. 10. The absolute values curves of the experimental signals from geometrically distorted lines before (*a*) and after correction (*b*) (*MN*1 line at Site 1): the notation shows the value of the offset of proximal end of *MN* line from the central position, in meters.

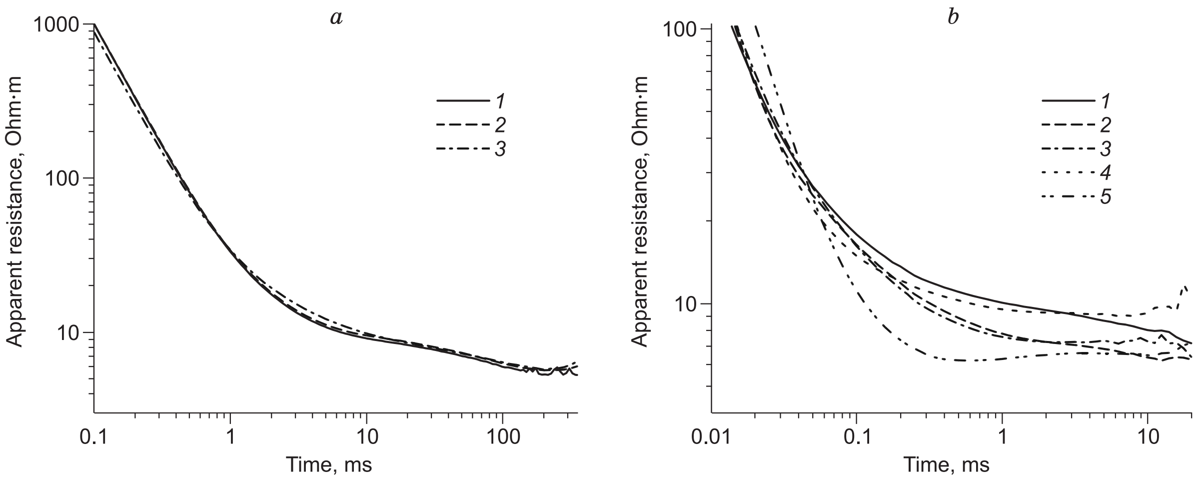

Fig. 11. Apparent resistivity curves for "extensive" central coaxial soundings (*a*): 1, Site 1, in 2018, 2, Site 1, in 2019, 3, Site 2, in 2019. Apparent resistivity curves for shallow coaxial sounding at the distal ends of the radial *MN* lines in the center of Site 2 in 2019 (*b*): *1*, central loop, *2,* distal end of *MN*1 line, *3*, distal end of *MN*2 line, *4*, distal end of *MN*3 line, *5*, distal end of *MN*4 line.

the signals at the late times for the component E_φ are related to noises produced by pulses and wind, which are inevitable companions of the measurements using grounded lines.

The curves interpretation and analysis generally indicate that the total longitudinal conductivity of all curves a depth of ~300 m is ~ 30 S, which implies that for large loops, all these differences are integrated into the upper part of the section, to be interpreted as an equivalent section. Given that our transmitter-receive lines system covers the area sized 3500×3500 m (the area covered by sounding is even wider), these near-surface heterogeneities do not affect the results. Analysis of a priori data derived from VES, seismic exploration, and drilling in the study area enabled identification of changes in the section within the first 300 m, while deeper down, the section is found to be remarkably persistent and laterally homogeneous, which is corroborated by our TEM studies using small loops.

The 3D mathematical modeling was also performed for estimation of the effect of the parameter variations in shallow subsurface on voltage in the *MN* lines, which showed that the signals induced by such variations do not exceed 1 μV over the entire period of measurements, i.e., heterogeneities in the near-surface cannot be the source of the signals registered by our *MN* lines.

THE HALL CONDUCTIVITY MEASUREMENTS

The current stage of research aims is to establish the fact of the geomagnetic effect manifestation. Of course, there should be a theory behind the experimental results. All in all, electrodynamics has been explored fairly well in mixed transverse electric (TE) and transverse magnetic (TM) fields in the course of the development of the theory underlying

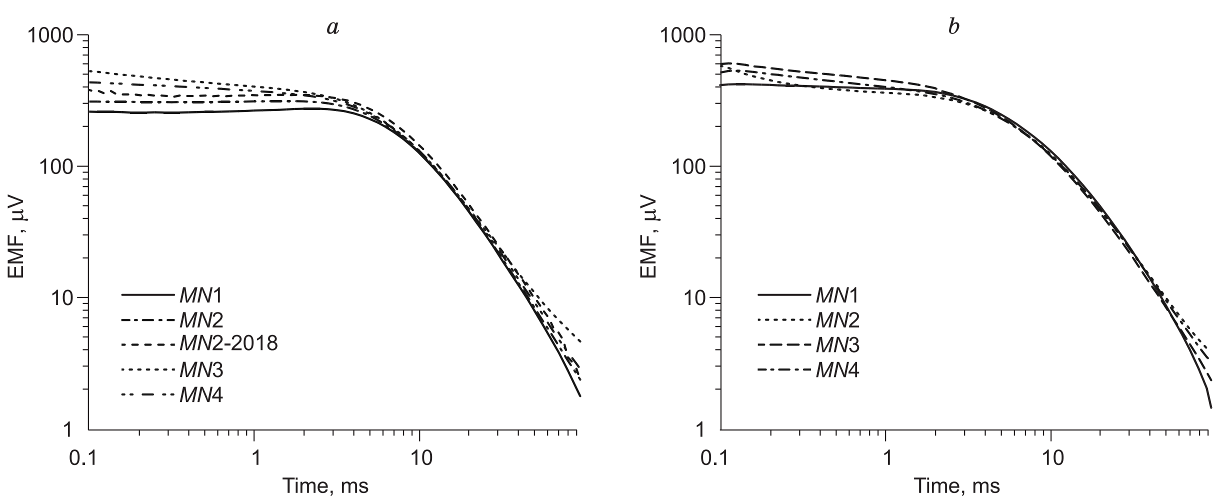

Fig. 12. TEM curves for the E_φ components of the field measured at proximal ends of the *MN* radial lines at Site 1 in 2018 and 2019 (*a*) and at Site 2 (*b*).

the Hall effect or, for example, magnetohydrodynamics (MHD) (Ginzburg, 1967; Landau and Lifshits, 1982; Kuchis, 1990). However, the problem is that effects are largely governed by the micro-level processes in a medium. Concerning to the geological, highly diverse, environment, it appears almost hopeless to take all this into account. The solution to this problem is to introduce effective parameters or a parameter that are/is determined empirically. Which is the case for electrical resistivity.

Thus, the transient process of a horizontal current loop in a horizontally layered medium will enjoy axial symmetry. The well known solution would be a pure TE-mode with the components H_r, H_z and a single electrical component E_φ.

However, the external (considering only the vertical H_z^0) magnetic field induces radial currents through the Lorentz force

$$j_r = \nu \cdot H_z^0 \cdot E_\varphi = \sigma_\mathrm{H} \cdot E_\varphi \,, \tag{1}$$

where σ_H is the Hall conductivity. Due to the currents closure in vertical planes, they are responsible for excitation of the TM mode and the magnetic field component H_φ. Thus, now the general solution contains both modes "sustaining" each other, and strictly speaking, there is no separation of the modes. Understandably, the Hall conductivity σ_H is, however, small, while the excited TM mode is weak. We can consider separately the main TE transient process and TM-process having an "exotic" current (1) as its source, where we replace the full field E_φ with the normal field E_φ^TE.

For the generated TM mode, we have a problem in which the first Maxwell equation can be written as

$$\mathrm{rot}\,\mathbf{H} = \sigma\mathbf{E} + \mathbf{j}_\mathrm{ext} \,, \tag{2}$$

where $\mathbf{H} = \{0, H_\varphi, 0\}$, $\mathbf{E} = \{E_r, 0, E_z\}$,

$$\mathbf{j}_\mathrm{ext} = \{\sigma_\mathrm{H} E_\varphi^\mathrm{TE}(r,z), 0, 0\} .$$

This problem can be solved, for instance, for a layered medium, knowing σ_H in each layer (but how do we know?!). In the first, roughest approximation, without accounting for the transient behavior of TM mode *per se*, the radial electrical gradient of the TM field will be determined as

$$E_r^\mathrm{TM} \approx \frac{\sigma_\mathrm{H}}{\sigma} \cdot E_\varphi^\mathrm{TE} \,, \tag{3}$$

which will be sufficient for us to propose a method for evaluation of the emerging TM mode. Thus, in the first approximation, the following expression holds for the voltage drop between points r_1 and r_2:

$$\Delta U = \frac{\sigma_\mathrm{H}}{\sigma} \cdot \int_{r_2}^{r_1} E_\varphi^\mathrm{TE} dr \,, \tag{4}$$

where σ is the ordinary conductivity of the medium, while the function of E_φ is a well-known solution for a horizontally layered medium without taking account of the geomagnetic factor. The integral is also readily calculated from the function. Now, by comparing the field measurements and the theoretical calculation for the aforesaid horizontal-layered medium (Table 1), we estimate the Hall conductivity. Given a fairly approximate nature of formula (4), σ will be taken as the average value of conductivity in the entire cross-section (about 10 Ohm·m). Figure 13 also shows a theoretical curve (in the group of field curves) calculated by the formula (4) at $\sigma_H = 0.002$ S/m.

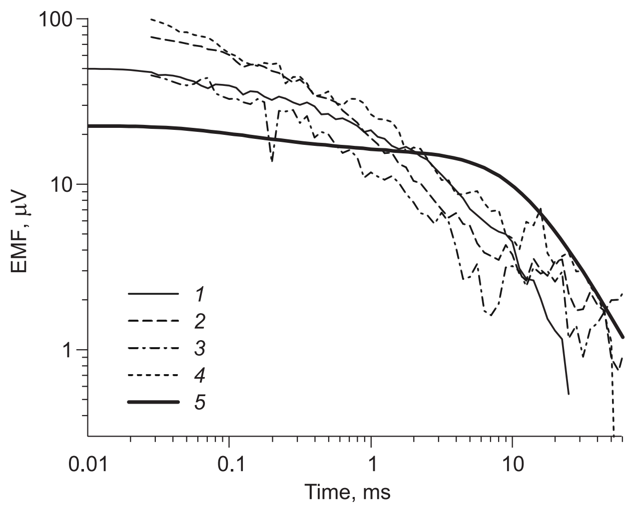

Fig. 13. Measured (*1–4*) and theoretical (*5*) transient signals in real *MN* lines at Site 1.

We have thus determined the Hall conductivity. The value of $\sigma_H = 0.002$ S/m is appropriate to us yet more because it is consistent with the research results (Plotkin et al., 2019), where the Hall conductivity is derived from the magnetotelluric (MT) data. Nevertheless, the inclination pattern of the theoretical curve differs slightly. This might be the implication of our neglecting the secondary "Hall" currents in formula (3).

CONCLUSIONS

This experimental study is a pioneering effort to detect and investigate the Hall effect in the geological environment. Reasoning from the preliminary data interpretation and the opinion of the researchers involved, this goal has been achieved.

The Hall conductivity is estimated to be ~$2\cdot10^{-3}$ S/m. The obtained results reliability has been confirmed by repeated measurements, additional experimental studies, and by testing the obtained material for compliance with the theory and mathematical modeling.

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