Available online at www.sciencedirect.com

SciVerse ScienceDirect

RUSSIAN GEOLOGY AND GEOPHYSICS

Russian Geology and Geophysics 53 (2012) 1243–1251

www.elsevier.com/locate/rgg

Testing TEM systems using a large horizontal loop conductor

N.O. Kozhevnikov *

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

Received 28 August 2011; accepted 16 February 2012

Abstract

Testing TEM systems has to include field experiments with physical models commensurate to the real transmitter–receiver configurations and to the target subsurface features. A large horizontal loop closed across a known resistance is a convenient model in this respect. It is convenient to lay in the field, it has manageable parameters, and its natural response is easy to calculate.

A field-size experiment and numerical modeling were applied to investigate the model wire loop response to eddy current in a uniform conductive ground, both at early and late times. The higher the resistivity of the ground the larger the time range in which the measured response matches the predicted one, other things being equal.

The experiments show that (i) closed loops laid near a transmitter–receiver system are applicable to test the quality of the latter as a tool for TEM or other similar resistivity surveys; (ii) current induced in the model loop can be used to infer the resistivity of the ground; (iii) a closed loop slows down the growth and reduces the amplitude of voltage induced at early times in a receiver loop or in a multiturn coil.

Keywords: TEM surveys; ungrounded horizontal loop; physical model

Introduction

Systems for resistivity surveys are commonly tested by measuring responses with managed parameters, most often voltage generated by a standard transmitter. In TEM surveys (Fig. 1, *a*), this is decaying emf (voltage) measured at the input of a data acquisition device (DAQ). It forms as an analog signal (e.g., with an RC circuit) or as a digital signal converted subsequently to the analog form. With this approach, the receiver unit only is tested.

Physical modeling of a reference transient response (Zakharkin and Tarlo, 1999) employs emf induced in a receiver loop by eddy current that arises in the model loop after the transmitter current is turned off (Fig. 1, *b*), the physical models and the tested systems being rarely larger than fractions of a meter. This modeling provides an idea, proceeding from similarity criteria, of how the real responses of ground and anomalous subsurface features may be. Another advantage is that this modeling tests the whole transmitter–receiver system rather than the receiver unit alone.

In the physical modeling method, a TEM system is configured as a series of four-poles, with transmitter and receiver loops, a synchronization line/channel or a conductor, power units, transportation units, and a ground. The constituent units are usually considered as linear four-poles with lumped parameters (Vishnyakov and Vishnyakova, 1974; Zakharkin, 1981) the latter being assumed to be independent of one another and invariable in time. In theory such a model represents a linear system, which is presumably stationary and free from cross couplings. In terms of application it corresponds to the approach that the instruments and the acquisition and processing techniques are designed by separate noncommunicating groups of people without due regard to interaction among the system constituents.

If a test system in a laboratory measures model transient responses to a wanted accuracy, does it mean that the field results may be expected to be as good? Answering the question may require additional studies though.

The transmitter and receiver loops, as well as the instruments together with the ground beneath them, make up a system of mutually interacting elements with distributed parameters (Kozhevnikov, 2006, 2009; Kozhevnikov and Nikiforov, 1998, 2000). The results depend on the resistivity of the ground, temperature, weather, electromagnetic noise, etc. Furthermore, the measuring unit and the receiver loop have their natural responses arising as the transmitter current turnoff causes overvoltage. The elements of the system interact

* Corresponding author.
E-mail address: KozhevnikovNO@ipgg.nsc.ru (N.O. Kozhevnikov)

1068-7971/$ - see front matter
http://dx.doi.org/10.1016/j.rgg.2012.09.010

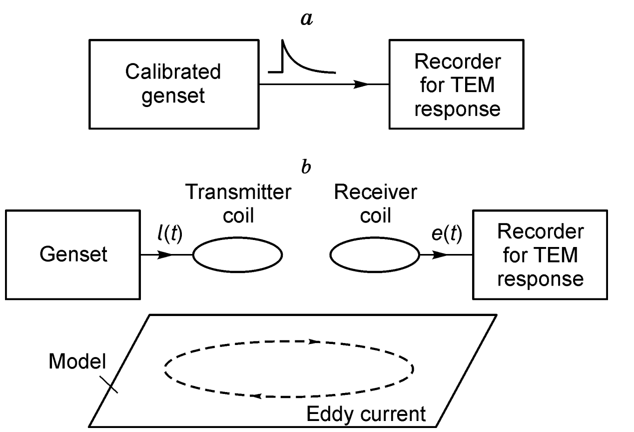

Fig. 1. Testing a measurement unit in a TEM system using a calibrated voltage source (*a*) and both transmitter and measurement units using a laboratory-scaled model of a conductor (*b*).

in different ways in laboratory and field conditions. The problems are largely due to gaps in the theory of similarity for electromagnetic systems: the known similarity criteria that relate laboratory and field data miss the specificity of the transmitter–receiver configuration as a complex system with distributed parameters. Note also the important role of the ground (especially, the shallow subsurface) which brings the separate elements together into a single system with its qualities different from a mere sum of qualities of each constituent.

The existing testing approaches in TEM surveys are designed to test separately the transmitter and receiver coils, without regard to a real system, assuming the latter to be defined by the receiver parameters. However, the proper testing method obviously has to address the system as a whole and to include field experiments not to miss some interfering effects. No proper testing is possible when confined to a small laboratory model with an electronic circuit or a small calibrating transmitter loop.

The available methods take no account of natural responses of the system "loop–shallow ground" and are applicable to TEM surveys if the loop self responses are much weaker than the measured responses of the ground (if it is conductive and if loop sizes are large). However, they fail in the case of resistive terrains, small loop sizes, and/or early-time measurements.

Suggested approach

A transmitter–receiver system can be tested according to its inductive coupling with a closed model loop laid nearby (Grant and West, 1965). A large ground loop was used, for instance, to calibrate and test time-domain airborne electromagnetic (AEM) systems was reported in (Davis and Macnae, 2008a,b). Horizontal ungrounded loops as such models of conductors must be applicable to testing ground TEM systems as well. It is important that natural responses of transmitter and receiver loops themselves are the same as in usual field surveys. This kind of testing can highlight the limitations that may elude detection by the common "soft" testing. The calibrating ground loop in the AEM systems of Davis and Macnae (2008a,b) was laid on resistive ground (10^3 ohm·m) and had its self-response much stronger than that of the ground. Testing TEM systems on a more conductive earth, however, requires a proper choice of the time interval in which the response of the ground remains smaller than that of the model conductor.

The field testing system we suggest (Fig. 2) consists of a model loop (*2*) laid near a transmitter (*1*) and a receiver (*3*) ones. The model loop is connected to the circuit with known impedance Z, which can be complex and frequency-dependent. In the simplest case, especially interesting in terms of practice, the loop is closed across an ordinary resistor with the resistance R. The loops in Fig. 2 are square but they may be of any geometry and relative position.

Each loop in Fig. 2 is inductively coupled to the two other loops, with the mutual inductances M_{12} between the transmitter and the model, M_{23} between the model and the receiver, and M_{13} between the transmitter and the receiver.

Assume that the rather long-lasting transmitter current $I_1 = I_0$ is turned off at the time $t = 0$ and decays linearly. The turn-off has the duration t_{off} (Fig. 3, *a*), proportional to loop inertia; the shorter the t_{off} the closer the current waveform to the step function $I_1(t) = [1 - \sigma(t)]\, I_0$, where $\sigma(t)$ is the unit Heavyside function.

Eddy current induced in a resistive ground (high resistivity ρ) decays fast and causes no marked effect on the current I_2 in the model loop. The transmitter current induces the synchonous primary magnetic flux B_1 which remains constant till $t = 0$ and then decays linearly to zero for the time t_{off}, and remains zero till the following turn-on pulse (the turn-on is not shown in Fig. 3, *a*). The linearly decaying magnetic flux generates an eddy current (electric filed E_1) around the transmitter described by Faraday's law of induction, which has a square waveform. The integral of the tangent component of E_1 over an arbitrary closed loop gives its induced emf. The emf $e_{12}(t)$ generated in the model loop (Fig. 3, *b*) lasts for the time t_{off} and is

$$e_{12}(t) = -M_{12}\frac{dI_1}{dt} = M_{12}\frac{I_0}{t_{\text{off}}},\ 0 < t \le t_{\text{off}}; \qquad (1a)$$

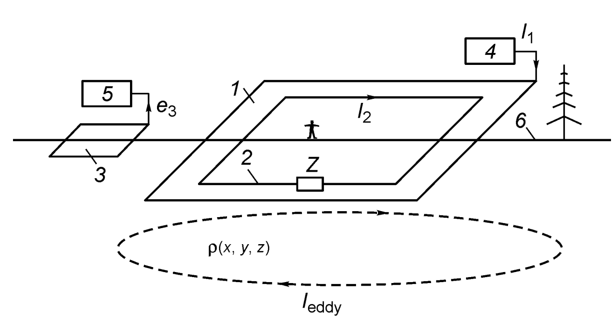

Fig. 2. Testing a TEM system: *1*, transmitter loop; *2*, model loop closed across impedance Z; *3*, receiver loop; *4*, transmitter unit; *5*, measurement unit; *6*, ground surface.

$$e_{12}(t) = 0,\ t > t_{\text{off}}. \tag{1b}$$

If $t_{\text{off}} \to 0$, i.e., in the case of instantaneous turn-off ($t_{\text{off}} \ll \tau$, where τ is the model time constant),

$$e_{12}(t) = M_{12} I_0 \delta(t),$$

where $\delta(t)$ is the delta function.

As a simple derivation shows, the current $I_2(t)$ the emf e_{12} generates in the model loop (see (1a), (1b) and Fig. 3, *b*) first grows and then decays:

$$I_2(t) = \frac{M_{12} I_0}{t_{\text{off}} R_m}\left[1 - e^{-t/\tau}\right] \text{ at } 0 < t \le t_{\text{off}}, \tag{2a}$$

$$I_2(t) = \frac{M_{12} I_0}{t_{\text{off}} R_m} e^{-t/\tau}\left[e^{t_{\text{off}}/\tau} - 1\right] \text{ at } t > t_{\text{off}}, \tag{2b}$$

where R_{m} is the model loop resistance that comprises the resistances R_{w} of the wire and R of the resistor:

$$R_{\text{m}} = R_{\text{w}} + R; \tag{3}$$

the time constant τ is

$$\tau = L / R_m, \tag{4}$$

where L is the self inductance of the model loop.

The current I_2 in the model loop induces a magnetic field which, in turn, generates the emf $e_{23}(t)$ in the receiver loop. This voltage normalized to the transmitter current (Fig. 3, *c*) is

$$\frac{e_{23}(t)}{I_0} = -\frac{M_{12} M_{23}}{L}\frac{1}{t_{\text{off}}} e^{-t/\tau},\quad 0 < t \le t_{\text{off}}; \tag{5a}$$

$$\frac{e_{23}(t)}{I_0} = \frac{M_{12} M_{23}}{L}\frac{1}{t_{\text{off}}} e^{-t/\tau}(1 - e^{t_{\text{off}}/\tau}),\quad t > t_{\text{off}}. \tag{5b}$$

At instantaneous turn-off ($t_{\text{off}} \to 0$), equations (5a) and (5b) can be joined into a single one that describes the model loop transient response $h(t)$:

$$h(t) = \frac{M_{12} M_{23}}{L}\left[-\delta(t) + \frac{1}{\tau} e^{-t/\tau}\right]. \tag{6}$$

The sum of $e_{13}(t)/I_0$ and $e_{23}(t)/I_0$ gives the current-normalized total emf $e_3(t)/I_0$ generated in the receiver by both the transmitter and model loop currents (Fig. 3, *d*):

$$\frac{e_3(t)}{I_0} = \frac{1}{t_{\text{off}}}\left(M_{13} - \frac{M_{12} M_{23}}{L} e^{-t/\tau}\right),\quad 0 < t \le t_{\text{off}}; \tag{7a}$$

$$\frac{e_3(t)}{I_0} = \frac{1}{t_{\text{off}}}\frac{M_{12} M_{23}}{L}\left(1 - e^{t_{\text{off}}/\tau}\right)e^{-t/\tau},\quad t > t_{\text{off}}. \tag{7b}$$

The transition to the limit at $t_{\text{off}} \to 0$ in (7b) gives $e_3(t)/I_0$ at the instantaneous turn-off:

$$\frac{e_3(t)}{I_0} = \left(M_{13} - \frac{M_{12} M_{23}}{L}\right)\delta(t) + \frac{1}{\tau}\frac{M_{12} M_{23}}{L} e^{-t/\tau}. \tag{8}$$

In the above derivation, the three loops (the transmitter, receiver, and model ones), were assumed to lie upon a resistive ground. This is the only case when the voltage measured at the time $t \ge t_{\text{off}}$ after the turn-off (see equation (7b)), is defined uniquely by the model loop response. Hereafter we denote this response as $e_{\text{m}}(t)$, and use I instead of I_0 for the transmitter current, according to the explanation above (Fig. 3).

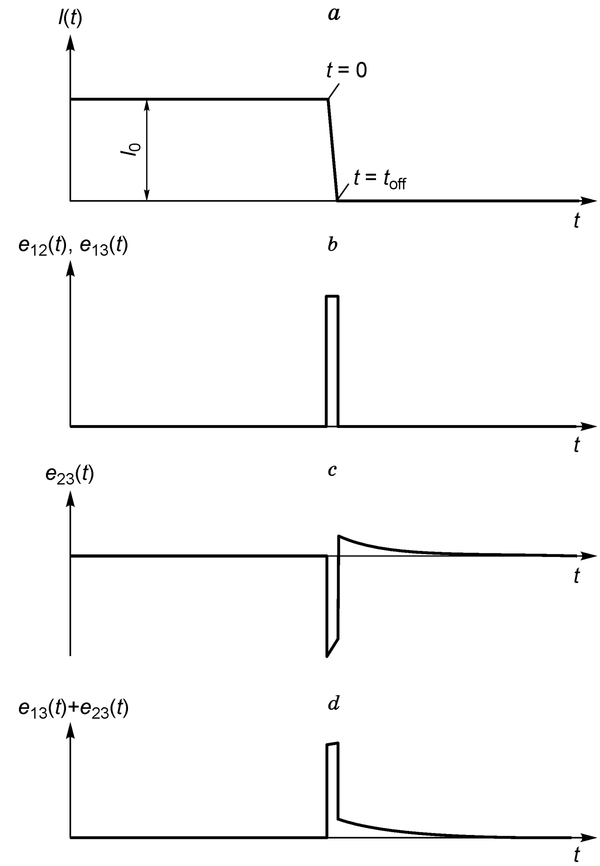

Fig. 3. Current and voltage in different elements of the TEM system (not to scale): (*a*) transmitter current; (*b*) model- and receiver-loop responses $e_{12}(t)$ and $e_{13}(t)$ to transmitter current turn-off; (*c*) receiver-loop response $e_{21}(t)$ to current decay in model loop; (*d*) total response at receiver. See voltage and current waveforms in different elements of the system.

Note. The current I can change as a function of the parameters of batteries or other transmitter current sources. For the measurement results to be comparable, the transients have to be normalized to the transmitter current at which the voltage is measured. (The response is written in the normalized form ($e_{\text{m}}(t)/I$, etc.) in the equations below.) Although being always denoted as I, the current may be different in different measurement sessions.

In real conditions, the ground is often conductive, and the response to the transmitter current turn-off includes the contributions from both the model loop and the ground, i.e., it depends on eddy current in the ground, besides the parameters of the three loops. We denote the current-normalized voltage the ground eddy current induces in the receiver as $e_{\text{g}}(t)/I$ and that induced by the transient current in the loop including the effect of the ground as $e_{\text{mg}}(t)/I$.

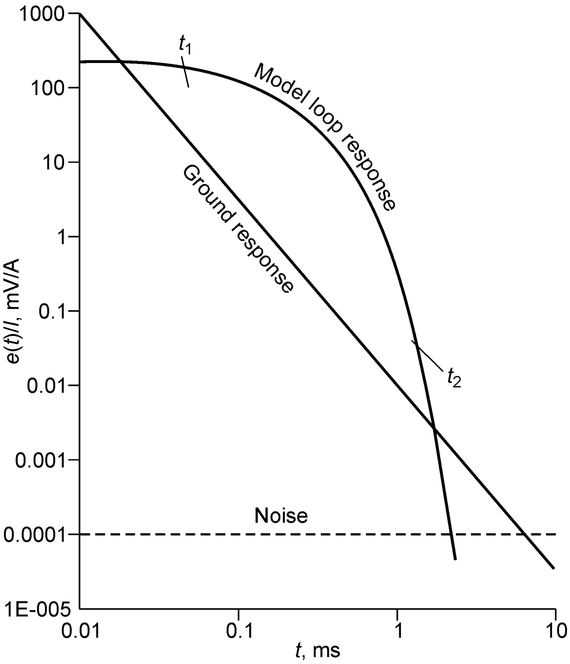

Fig. 4. Natural self responses of ground and model loop, in absence of mutual inductance.

The response $e_{g+m}(t)/I$ in the system 'ground + model' can be written as the sum $e_{g+m}(t)/I = e_g(t)/I + e_{mg}(t)/I$, wherefrom it follows that

$$e_{mg}(t)/I = e_{g+m}(t)/I - e_g(t)/I. \quad (9)$$

Unlike $e_m(t)/I$, in the general case, $e_{mg}(t)/I$ bears the effect of conductive ground. Therefore, it is important to see whether it is possible (and if yes, at which parameters of the system and the ground) to configure the test system in a way to reach $e_{mg}(t)/I \approx e_m(t)/I$.

If these conditions are found, testing measurement systems can be rather straightforward, though confined within a limited time interval. The procedure is to measure, while the model loop is open, the voltage $e_g(t)/I$ the ground eddy current induces in the receiver loop and then the response $e_{g+m}(t)/I$ of the 'ground + model' system after the model loop is shorted across a resistor. The voltage $e_m(t)/I$ is calculated by subtracting the ground response from that of the 'ground + model' system:

$$e_m(t)/I = e_{g+m}(t)/I - e_g(t)/I. \quad (10)$$

Finally, thus found response is compared with the one predicted with (7b), and their difference shows the quality of the tested TEM system.

The predicted transient responses of a uniform conductive ground and a model loop in Fig. 4 illustrate the case when the ground component is smaller than the model one. At late times, the emf the eddy current decay in a uniform conductive ground induces in the receiver loop is a power function (Sidorov, 1985; Spies and Frischknecht, 1991):

$$e_r(t)/I = a \cdot t^{-5/2}, \quad (11)$$

where a is a time-independent coefficient which accounts for the system geometry and the ground conductivity. The voltage induceed in the receiver loop by current decay in the model loop is the exponent

$$e_m(t)/I = b \cdot \exp(-t/\tau), \quad (12)$$

where τ is the time constant of the model loop response and b is a time-independent coefficient (see equation (7b)).

The log–log plot of the power function is a straight line with the slope ratio –5/2. The log–log exponential function plots like a convex curve with its slope increasing with time. The choice of the parameters M_{12}, M_{23}, L, and τ can lead to a given excess (ten times and more in Fig. 4) of the voltage in the receiver over that induced by the eddy current decay in the ground within the time window $t_1 - t_2$. Thus, the response measured to a given accuracy in the range $t_1 - t_2$ is defined by the parameters of the model loop. Table 1 lists the parameters the user can manage directly or indirectly. They enter equations (2)–(8) which describe the model loop response to the turn-off.

The horizontal line in Fig. 4 shows instrument and extrinsic noise. As time elapses, the signal/noise ratio for the exponential model decreases more rapidly than that for the conductive ground response.

Field experiments: methods and results

Special field experiments were performed at test sites in the vicinity of Mirny city in western Yakutia in order to see whether the superposition principle fulfills in the case of testing a TEM system with a large loop and within which time range if it does. We used coincident loop configurations, with both loop and multiturn coil receivers and square model loops of a standard geophysical copper wire laid coaxially with the transmitter and receiver loops. The resistance in the model circuit was managed using a resistance bridge. The responses were excited and recorded using a commercially available instrument *Tsikl-5* (Russian for *Cycle*). A series of measurements was applied at each point with different resistances R in the range from ∞ (open model loop) to 0 (closed loop). The response of the ground $e_g(t)/I$ was measured at $R = \infty$ and the response $e_{g+m}(t)/I$ of the system 'ground + model' was measured when the model loop was shorted across a resistor; then the difference was calculated by (9).

Figure 5 illustrates typical results from vicinities of the XXIII CPSU Congress kimberlite. The local geology consists of Jurassic sand and clay sandwiched between thin Quaternary

Table 1. Controlled parameters of ungrounded model loop closed across a resistor

Parameter	Causes effect on
Size	L, M_{12}, M_{23}, R_w
Position relative to transmitter and receiver	M_{12}, M_{23}
Wire	R_w, τ
Resistor R	τ

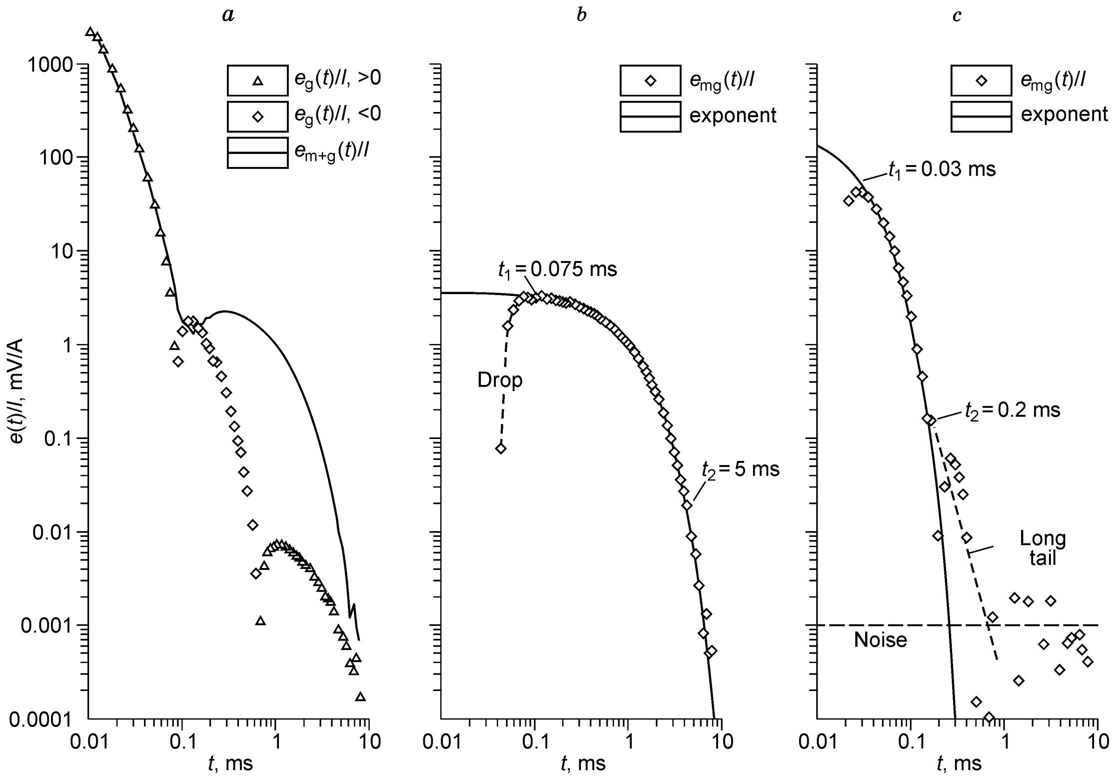

Fig. 5. Results of a field experiment in vicinity of XXIII CPSU Congress kimberlite. *a*: Open loop ($R = \infty$) and shorted ($R = 0$) model loop transients; *b* and *c*: $e_{mg}(t)/I$ and envelopes for $R = 0$ (*b*) and $R = 20$ ohm (*c*). 100 m × 100 m coincident loop; 50 m × 50 m model loop of copper wire laid at the center of a transmitter–receiver system. The exponent fitted using $e_{mg}(t)/I$ over the time interval from t_1 to t_2.

sediments above and Lower Paleozoic terrigenous-carbonate sediments below. The resistivity profile at the site, to a depth about 200 m, corresponds to a conductive (100–200 ohm·m) uniform polarizing earth, according to TEM surveys with a central-loop configuration of a 100 m × 100 m transmitter and a 50 m × 50 m receiver (Kozhevnikov and Antonov, 2008).

The left panel in Fig. 5, *a* shows measured responses, the $e_g(t)/I$ one being from the ground (open model loop, $R = \infty$). Due to polarization, responses from near-surface frozen ground bear effects of fast decaying IP, which show up as sign reversals and/or monotony break (Kozhevnikov and Antonov, 2008). That is why, there is a time interval where the $e_g(t)/I$ curve is negative. Another curve in Fig. 6, *a* shows the emf $e_{g+m}(t)/I$ induced in the receiver when the model loop is closed ($R = 0$).

The curve $e_{mg}(t)/I$ in the middle of Fig. 5, *b* is the difference between the responses in the left panel and the approximating exponent (envelope). The curve $e_{mg}(t)/I$ and the envelope in the right panel in Fig. 5, *c* are for the case when the model loop is closed across a 20 ohm resistor. When searching the exponent, only the interval between t_1 and t_2 was used, in which the exponent fitted well the measured response and $e_{mg}(t)/I$ was approximately $e_m(t)/I$. Therefore, the straightforward testing method is reasonably applicable within this interval.

At early ($t < t_1$) and late ($t > t_2$) times, $e_{mg}(t)/I$ depart from the exponential pattern. At early times, the voltage $e_{mg}(t)/I$ drops abruptly with respect to the envelope and is negative at the earliest times (the negatives are not shown in the log–log plots). All measurements at different sites with different loop configurations and models indicate that the smaller the model time constant τ, the earlier the time where the potential drops to negative.

At late times, there is a long tail in the $e_{mg}(t)/I$ responses corresponding to slow potential decrease with respect to the exponential envelope (Fig. 5, *c*). The tail likewise appears at earlier times and is ever more prominent at ever smaller τ. According to measurements with different loop models and configurations, the voltage $e_{mg}(t)/I$ decreases proportionally to t^{-x} at $t > t_2$, where $x \approx 3$–4.

Effects of eddy current in the ground

At first, the negatives and the tails in the responses were attributed to instrument errors. However, $e_{mg}(t)/I$ departs from the exponent rather because it comprises closed-loop responses to eddy current in the ground.

Remember that resistive ground causes no effect on current decay in the model loop and emf created in the latter is restricted to the turn-off time (see equations (1a), (1b), and Fig. 3, *b*). This emf induces current described by equations (2a), (2b) while (7a), (7b) represent emf generated in the receiver loop by the decay of this current.

In Figure 6 the curves on the left are the model loop response and the curves on the right are the current waveforms predicted by (2a), (2b). The calculation is for a central-loop configuration, with a circular transmitter of the 50 m radius

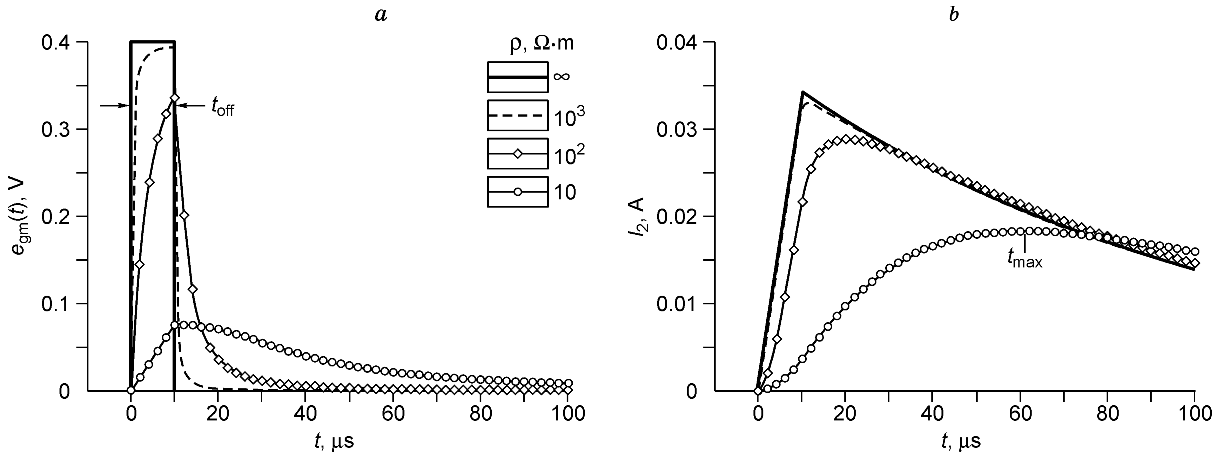

Fig. 6. Emf (*a*) and current decay (*b*) in model loop. Central-loop configuration, with radiuses 50 m (transmitter) and 10 m (receiver). Model loop of 10 m radius is coincident with receiver. Time constant $\tau = 100$ μs. Transmitter current amperage 1 A, $t_{\text{off}} = 10$ μs.

and a receiver of the radius 10 m; the model loop coincident with the receiver likewise has the radius 10 m. This loop size is chosen according to TEM systems commonly used in Yakutia. The transmitter current is assumed to be 1 A and the turn-off time to be 10 μs (this is the time required to stop current in a transmitter of the given size using the modern facilities, including a current pulse generator of *Tsikl-5*). The time constant of the model loop response is $\tau = 100$ μs.

In the considered idealized case (nonconductive ground), the model loop response is rectangular and has the duration t_{off}. For the selected t_{off}/ ratio, current in the model loop, within the 0 to t_{off} interval, grows almost linearly and then decays exponentially with the time constant τ.

As a rule, the TEM system and the model loop are laid upon conductive ground. It is reasonable to hypothesize that the model loop responds to both the transmitter current switch and the eddy current in the ground. Therefore, in order to calculate $I_2(t)$, one has to convolve $e_{\text{gm}}(t)$, the emf induced in the model loop by both transmitter loop current and eddy currents in the earth, with the current impulse response $i_2(t)$ of the model loop:

$$I_2(t) = e_{\text{gm}}\, t * i_2(t). \tag{13}$$

The waveform $i_2(t)$ describes the current induced by a very short voltage pulse of the area 1 V·s. For a loop closed across the resistance $R_{\text{m}} = R_{\text{w}} + R$,

$$i_2(t) = \frac{1\ \text{V}\cdot\text{s}}{L}\, e^{-t/\tau},$$

where $\tau = L/R_{\text{m}}$.

The $e_{\text{gm}}(t)$ curves in Fig. 6, *a* are calculated for three ground resistivities ρ (10, 10^2 and 10^3 ohm·m) using the analytical equation for the azimuthal component of the electric field from a vertical magnetic dipole upon a uniform conductive ground (Spies and Frischknecht, 1991), because the model loop radius is five times smaller than that of the transmitter. If the ground is low conductive, the emf induced in the model loop obviously lasts for a very short time (about 20 μs) and has a nearly rectangular waveform as in the idealized case of a nonconductive ground. At the resistivity ρ as low as 100 ohm·m, the voltage build-up slows down between 0 and 10 μs and fails to reach the value defined by equations (2a), (2b) at $t = t_{\text{off}}$ μs for the turn-off time. After the turn-off, the emf induced in the model loop continues for the first tens of μs. At a still lower resistivity (10 ohm·m), the voltage does not reach 0.1 V but its duration becomes as long as hundreds of μs.

Figure 6, *b* shows the $I_2(t)$ curves obtained by convolution of the current waveforms with the model loop emf from Fig. 6, *a*, assuming $\tau = 100$ μs. Current in the model loop upon a weakly conductive ground ($\rho = 10^3$ ohm·m) begins decaying right after the turn-off. At the time longer than t_{off}, eddy current in the ground likewise decays progressively. The receiver loop responds to the change rate (time derivative) of magnetic field which, in turn, is the sum of the magnetic field produced by eddy current in the ground and by the current $I_2(t)$ in the model loop. Inasmuch as both the eddy current in the ground and the current in the model loop decay, they contribute to the measured signal having the *same polarity* and, together, create emf in the receiver equal to the *sum* of emf induced by each component of the 'ground + model' system already at the earliest times.

As the ground becomes more conductive, the current buildup becomes longer (e.g., the current peaks at $t = 20$ μs when $\rho = 10^2$ ohm·m and at $t = 60$ μs if $\rho = 10$ ohm·m) and its decay slows down as well. Then, on increasing to the maximum at the time $t_{\max}$, current in the model loop changes at a rate *opposite* to that of eddy current in the ground. Thus, at the time $t < t_{\max}$, the voltage induced in the receiver loop is a *difference* of emf induced by the decaying eddy current in the ground and that induced by the model loop current. This is the reason why there are negatives in the measured model loop responses $e_{\text{mg}}(t)/I$.

It follows from Fig. 6, *b* that measured model loop transients can be used to infer the resistivity of the ground. It is unreasonable to discuss the advantages and the drawbacks of this way of estimating resistivity (e.g., the TEM system noise and performance) in the context of this paper. Note only

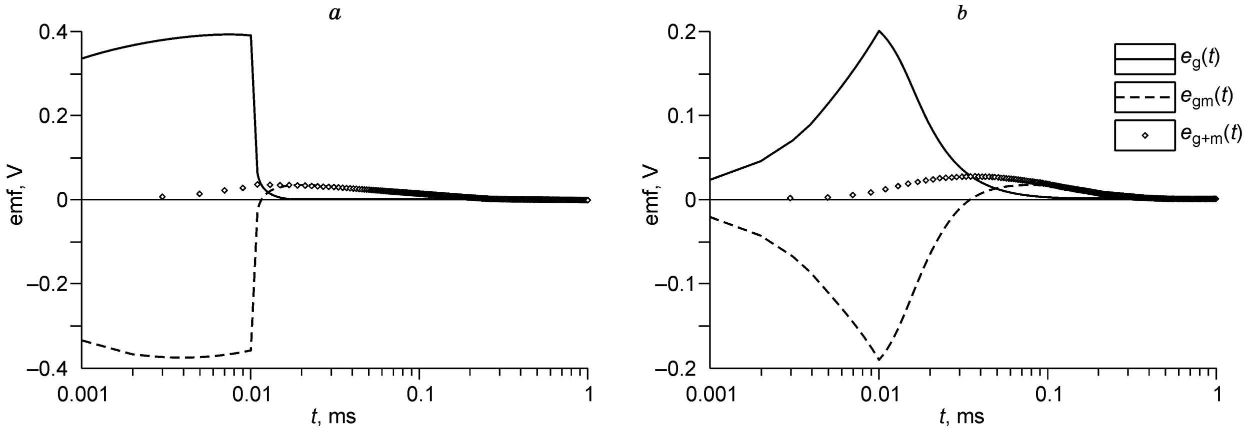

Fig. 7. Transient responses for $=10^3$ ohm·m (*a*) and 30 ohm·m (*b*). Central-loop configuration, with radiuses 50 m (transmitter) and 10 m (receiver). Model loop of 10 m radius is coincident with receiver. Time constant $\tau = 100$ μs. Transmitter current amperage 1 A, $t_{\text{off}} = 10$ μs.

that shorted loops have never been used so far in resistivity surveys though being used since long ago for EM measurements in conductive media (Zimin and Kochanov, 1985).

Commonly TEM surveys measure voltage in an open receiver loop rather than current in a closed loop. Therefore, it is more appropriate to discuss the modeling results as time-dependent emf shown in Fig. 7, *a* and 7, *b* for the mentioned loop size, turn-off duration, and time constant. Each figure shows three responses:

(1) receiver response to eddy current in the ground $e_g(t)$;

(2) receiver response to current change in the model loop $e_{mg}(t)$, given by

$$e_{mg}(t) = -M_{23}\frac{dI_2}{dt}. \tag{14}$$

In the case in point, the receiver loop is coincident with the model loop, and therefore $M_{23} = L$;

(3) total response $e_{g+m}(t) = e_g(t) + e_{mg}(t)$.

Mind that $e_g(t)$ and $e_{g+m}(t)$ are the responses measured in the field.

The curves in Figs. 7, *a* and Fig. 8, *b* are predicted responses of $\rho = 10^3$ ohm·m and 30 ohm·m ground, respectively. In both cases, the responses of the conductive ground and the model loop to the turn-off are similar in amplitude but opposite in polarity, especially, at the earliest times. Therefore, the total response to the turn-off $e_{g+m}(t)$ is first about zero and then increases smoothly till the values much less than those in the absence of the model loop; the lower the ground resistivity the longer the buildup time. As the time elapses, the contribution of the ground to the total response becomes ever lower than that of the model loop current. The total response peaks earlier in more resistive ground: at t = 20 μs for $\rho = 10^3$ ohm·m and at t = 100 μs for $\rho = 30$ ohm·m.

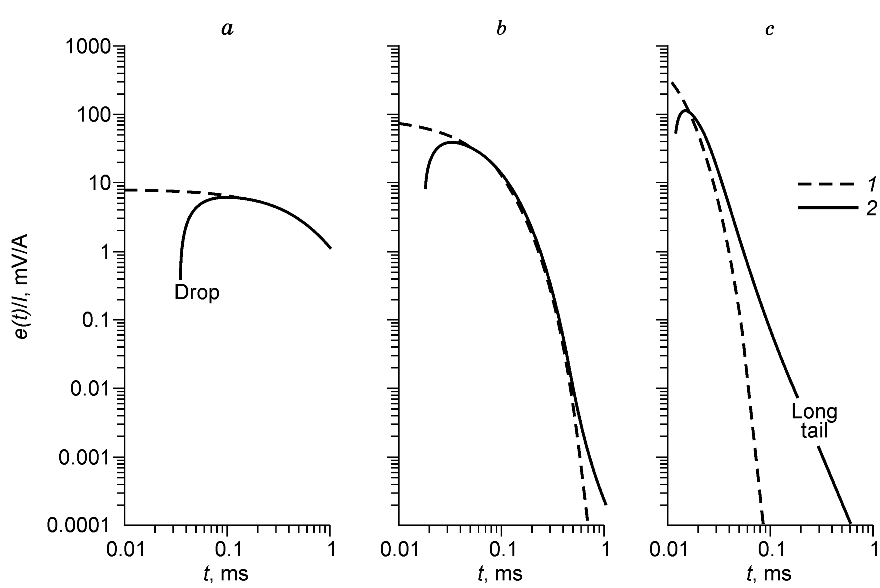

Fig. 8. A numerical experiment simulating field measurements: $e_m(t)/I$ is calculated model loop self-response of a nonconductive ground (*1*); $e_{mg}(t)/I$ is the same with response to eddy current in $\rho = 100$ ohm·m ground (*2*). Model time constant: 0.5 ms (*a*), 0.05 ms (*b*), 0.005 ms (*c*).

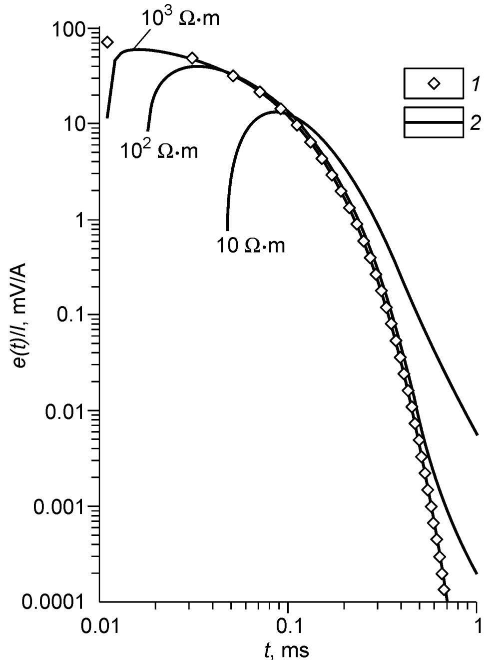

Fig. 9. Model loop responses of nonconductive (*1*) and conductive (*2*) ground. Central-loop configuration, with radiuses 50 m (transmitter) and 10 m (receiver). Model loop of 10 m radius is coincident with receiver. Time constant $\tau = 0.05$ ms. Transmitter current amperage 1 A, $t_{\text{off}} = 10$ ms.

Note again that the amplitude of the total response between $t = 0$ and $t = t_{\text{off}}$, i.e., during the turn-off time, is much less than that with an open model loop. Furthermore, the early-time turn-off effect on the receiver loop and the acquisition unit is smoother in the presence of a closed model loop. Therefore, the latter may act as a sort of a damper which may be useful when a TEM system stays long in suspension after the transmitter current turn-off because of overload (in the case of a resistive ground and/or in the case of too strong mutual inductance between the transmitter and receiver loops).

Figure 8 illustrates how $e_{\text{m}}(t)/I$ and $e_{\text{mg}}(t)/I$ behave at different time constants τ ($\tau = 0.5$, 0.05, and 0.005 ms) of current decay in the model loop, with the assumption of nonconductive ground ($\rho = \infty$) for $e_{\text{m}}(t)/I$ and $\rho = 10^2$ ohm·m for $e_{\text{mg}}(t)/I$. Note the similarity of the predicted $e_{\text{mg}}(t)/I$ responses with the measured ones (Fig. 5, *b*, *c*). At lower τ the difference between the ideal ($\rho = \infty$) and real ($\rho = 10^2$ ohm·m) model loop responses, which shows up as negatives and tails, appears at ever earlier times.

The long tail looks like a straight line in log–log plots. Therefore, the model loop response is the power function

$$\frac{e_{\text{mg}}(t)}{I} \propto t^{-x}. \qquad (15)$$

The approximation of long tails is the best at $x = 3.5$. Voltage in the receiver loop is proportional to the rate of I_2 change in the model loop, i.e., to its time derivative. That is why the current decays exponentially ($x = 2.5$) at late times, as well as the model loop (or receiver loop, or any other) response of a uniform conductive ground. The explanation is simple: the model loop inductance being smaller than the resistance at late times, the emf and the current it induces in model loop are synchronous.

At $\tau = 0.5$ ms and $\tau = 0.05$ ms, there is a time range in which the ideal ($e_{\text{m}}(t)/I$) and real ($e_{\text{mg}}(t)/I$) transients coincide and the straightforward testing procedure *becomes possible*. At small τ, and "real" model loop responses differ over the entire time interval (Fig. 8, *c*).

The transients in Fig. 8 are for different τ and $\rho = 10^2$ ohm·m. It is important also how the ground resistivity influences the model loop responses. See Fig. 9, with $\tau = 0.05$ ms, for the cases of nonconductive ($\rho = \infty$) and conductive ($\rho = 10$, 10^2 and 10^3 ohm·m) ground. As one may expect, weakly conductive ground ($\rho = 10^3$ ohm·m) contributes insignificantly, and the model loop response does not differ from that of a nonconductive ground over the entire range of times common to commercially available TEM systems. At a lower resistivity of 10^2 ohm·m, there appear both a drop (a negative) and a long tail, which restrict the interval in which $e_{\text{m}}(t)/I$ and $e_{\text{mg}}(t)/I$ coincide. At a still lower resistivity ρ, the model loop response that comprises the contribution from the ground progressively departs from the ideal one and deviates from the exponential pattern over the entire time interval.

Discussion

Thus, the suggested testing procedure is applicable as far as the model loop response remains independent of eddy current in the ground.

Assuming that the model loop self-response is the signal and the ground component is the noise, one has to design the TEM system in a way to hold the signal/noise ratio no lower than some acceptable value (10 or 10^2, etc.).

Other things being equal, the more resistive the ground the smaller its contribution to the total response (Fig. 9). Obviously, the larger the time range in which the system is tested, the higher the required resistivity of the ground.

In order to enlarge the decay time range, a set of models with different τ can be used. The time constant is small if the resistance that closes the model loop is large, which allows testing the measurement system at early times. If the resistance is low and the time constant is large, the system can be tested at late times. When decreasing τ one has to stay within the time range where $e_{\text{mg}}(t)/I = e_{\text{m}}(t)/I$ (Fig. 8).

The limitations associated with conductive ground can be cancelled (at least in principle) if the resistivity pattern of the study area is rather well known. For a terrain of known resistivity distribution, one can compute model loop responses $e_{\text{gm}}(t)$ using available software (e.g., *PODBOR* for a layered earth (Mogilatov et al., 2007), TEM-IP (Antonov et al., 2010), etc.)), then convolve them with the current waveforms $i_2(t)$ and find the voltage $e_{\text{mg}}(t)$ the model loop current induces in the receiver loop. Then the predicted current-normalized response ($e_{\text{mg}}(t)/I$) is compared with the measured one.

This method may appear too sophisticated at the first sight. Specifically, a question arises why using a model loop when the resistivity pattern is known instead of comparing the measured transients with those predicted for the known resistivity model. However, this approach is valid in simple resistivity settings and/or for large loop sizes when the target depths are relatively large. According to our years-long experience of TEM surveys in complex geophysical settings with high resistivity, polarization, magnetic viscosity, heterogeneity, or their combination, it is often hard to understand whether unusual transients are due to geology or to instrument limitations (Kozhevnikov and Antonov, 2008; Stognii et al., 2010; Vakhromeev and Kozhevnikov, 1988). The case becomes still more problematic with shallow depths (μs range), which requires small loop sizes (Kozhevnikov and Plotnikov, 2004).

This is exactly the case when a model loop is needed, with manageable parameters and a size commensurate with the target geological objects. This model allows designing and performing *controlled experiments* even in complex field conditions, to assess the time range, the loop size, the instrument specifications, and the acceptable errors to properly infer the local geology features, and to find the limits where the TEM system self-response becomes predominating. The efficiency of this approach in AEM surveys is demonstrated in (Davis and Macnae, 2008a,b).

The reported study was motivated by the necessity to find a method for testing a real TEM system laid on the ground. Besides justifying the method, the experiment provided new insights into the effect of conductive ground on the response of a confined conductor. An additional advantage is that a closed model loop slows down the growth and reduces the amplitude of the ground current contribution to the response functions of the receiver loop (or an induction multiturn coil). Furthermore, closed model loop responses can be used to infer the resistivity of the ground.

Finally, the reported model loop responses were calculated with regard to eddy current in the ground, but the back effect of the model loop on the eddy current has not been estimated, though this calculation is straightforward. However, the model loop can cause only a minor effect on the ground response because the current in it is within a few tens of mA at the 1 A transmitter loop current (Fig. 6, *b*).

Conclusions

The method of testing TEM measurement systems has to include field work with the use of model loops commensurate to the tested transmitter–receiver loop sizes and to the target geological objects.

An ungrounded horizontal loop connected to a known resistance is a convenient model for this purpose: It is easy to lay on the ground, to control its parameters, and to calculate its transient response.

The testing procedure is especially simple if the ground is definitely known to cause no significant influence on current decay in the model loop. Then it includes (1) calculating the model loop response $e_m(t)/I$ by equation (2b); measuring the voltages in the open (2) ($e_g(t)/I$) and closed (3) ($e_{m+g}(t)/I$) model loops; (4) calculating $e_{mg}(t)/I = e_{m+g}(t)/I - e_g(t)/I$; (5) comparing $e_{mg}(t)/I$ and $e_m(t)/I$.

If the ground is conductive and its eddy current interferes with the current decay in the model loop closed across a known resistance, the measured current can be used to infer the resistivity of the ground.

A closed model loop slows down the growth and reduces the amplitude of the ground current contribution to the response functions of the receiver loop (or multiturn coil).

I appreciate greatly the aid of V.A. Vanchugov and V.N. Novopashin in organizing and setting up field measurements. The manuscript profited much from constructive criticism by A.K. Zakharkin and an anonymous reviewer.

References

Antonov, E.Yu., Kozhevnikov, N.O., Korsakov, M.A., 2010. The TEM-IP software for processing IP-affected TEM data, in: Proc. GEOBAIKAL-2010, 1st Int. Conf. Electromagnetic Surveys. EAGE, Irkutsk, p. 2.

Davis, A.C., Macnae, J., 2008a. Quantifying AEM system characteristics using a ground loop. Geophysics 73 (4), F179–F188.

Davis, A.C., Macnae, J., 2008b. Measuring AEM waveforms with a ground loop. Geophysics 73 (6), F213–F222.

Grant, F.S., West, G.F., 1965. Interpretation Theory in Applied Geophysics. McGraw-Hill, New York.

Kozhevnikov, N.O., 2006. Ungrounded horizontal loops as systems with distributed parameters. Geofizika, No. 1, 29–39.

Kozhevnikov, N.O., 2009. Applying the transmission line theory to study ungrounded horizontal loop self transients. Russian Geology and Geophysics (Geologiya i Geofizika) 50 (3), 222–235 (300–316).

Kozhevnikov, N.O., Antonov, E.Yu., 2008. Inversion of TEM data affected by fast-decaying induced polarization: Numerical simulation experiment with homogeneous half-space. J. Appl. Geoph. 66, 31–43.

Kozhevnikov, N.O., Nikiforov, S.P., 2000. Early time TEM responses of an ungrounded horizontal loop—a new look. Proc. 62nd EAGE Conference, Expanded Abstracts, Glasgow, D-11.

Kozhevnikov, N.O., Plotnikov, A.E., 2004. Testing the TEM method for nearsurface applications. Geofizika, No. 6, 33–38.

Mogilatov, V.S., Zakharkin, A.K., Zlobinskii, A.V., 2007. Software for Inversion of Near-Field TEM Data. *Podbor* System [in Russian]. Akademicheskoe Izd. Geo, Novosibirsk.

Sidorov, V.A., 1985. Transient Electromagnetic Surveys [in Russian]. Nedra, Moscow.

Spies, B.R., Frischknecht, F.C., 1991. Electromagnetic sounding, in: Nabighian, M.N. (Ed.), Electromagnetic Methods in Applied Geophysics. SEG, Vol. 2, pp. 285–425.

Stognii, Vas.V., Kozhevnikov, N.O., Antonov, E.Yu., 2010. TEM surveys for magnetic viscosity of rocks in situ. Russian Geology and Geophysics (Geologiya i Geofizika) 51 (11), 1219–1226 (1565–1575).

Vakhromeev, G.S., Kozhevnikov, N.O., 1988. TEM Surveys for Mineral Exploration [in Russian]. Irkutsk University, Irkutsk.

Vishnyakov, A.E., Vishnyakova, K.A., 1974. Excitation and Measurements of Fields in Resistivity Surveys [in Russian]. Nedra, Moscow.

Zakharkin, A.K., 1981. Use of a *Tsikl* System for Near-field TEM Surveys: a Methodological Guide [in Russian]. SNIIGGiMS, Novosibirsk.

Zakharkin, A.K., Tarlo, N.N., 1999. Problems of near-field TEM surveys. Geofizika, No. 6, 34–39.

Zimin, E.F., Kochanov, E.S., 1985. Measurements of Electric and Magnetic Fields in a Conductive Earth [in Russian]. Energoatomizdat, Moscow.

Editorial responsibility: M.I. Epov