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Software for inversion of TEM data affected by fast-decaying induced polarization

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Abstract

The paper presents new software and stepwise modeling techniques for inversion of TEM data affected by fast-decaying induced polarization (IP). The software and the methods have demonstrated high efficiency when applied to detection of unfrozen ground zones (taliks) in the Pyakyakhinka oilfield and to petroleum exploration in the southern Siberian craton.

Keywords: induced polarization; joint inversion; TEM surveys; permafrost

Introduction

The earliest software for processing and interpretation of transient electromagnetic (TEM) data appeared in the 1980s and became popular in geophysics, especially with the advent of personal computers. The best known were the *GRENDL* (McAllister and Raiche, 1986), *TEMIX* (Stoyer, 1988), *ERA* (Epov et al., 1990; Tabarovsky and Epov, 1990; Tabarovsky et al., 1989) and *PODBOR* (Mogilatov et al., 2007) programs designed for layered-earth forward and inverse modeling of airborne TEM data.

The recent advanced software packages for ground TEM surveys include:

EMS (IPGG, Novosibirsk), an updated version of *MFS ERA+* (Epov et al., 1990; Tabarovsky et al., 1989) for 2D data (Khabinov et al., 2010). The new version has an upgraded user interface and graphic visualization options. Inversion is performed with an assumption of a conducting layered earth, while forward modeling employs the thin film model of Price-Sheinman with a layered earth approximated by a system of *S*-films (Tabarovsky and Epov, 1990).

PODBOR (SNIIGGiMS, IPGG, Novosibirsk), a software (Mogilatov et al., 2007) employing Tokhonov's time-domain fast forward algorithm (Tikhonov and Skugarevskaya, 1950) besides the frequency-domain code. The software supports four inversion methods (Levenberg–Marquardt, Newtonian, linear inversion with the Taylor local series, and minimization using a linearized forward model), and has an advanced smooth-running service support.

EM Vision (*Encom*, Australia), a program suitable for processing IP-affected TEM data, with its interface adjusted to different acquisition systems: *Artemis*, *Geonics*, *Sirotem*, *Zonge Engineering*, *Airborne GEOTEM* etc. (web2.encom.com.au/pages/swev_sp.htm).

EMIGMA (*PetRos EiKon* Inc., Canada), a package including tools for processing central-loop or loop-loop airborne and ground TEM data, as well as a 3D modeling tool. Inversion is run with the Okkama and Marquardt layered-earth algorithms. It features an advanced graphical interface comparable with special data visualization systems (www.petroseikon.com/emigma/77ps/tem.php).

TEM-RESEARCHER (*Applied ElectroMagnetic Research* (AEMR), The Netherlands), a program making part of the *TEM-FAST 48HPC* multipurpose geophysical system. The program provides fast inversion of layered-earth and gradient sections, even those affected by IP and superparamagnetic (magnetic viscosity) effects. It has special tools for 2D- and/or 3D-imaging of geoelectrical sections and a tool for joint inversion of TEM and DC data (Barsukov et al., 2007).

STEMINV (*Zonge International* Inc., USA), a software for smooth-model inversion of multi-frequency TEM data acquired with *Zonge* instruments. TEM data are processed with the use of a TEM1D module for modeling loop TEM responses and a TCINV module for layered-earth inversion

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with iterative linear minimization algorithms (www.zonge.com/ModelTEM.html).

SiTEM/SeMDI (*Aarhus Geophysics*, Denmark), a system of two packages for processing (SiTEM) and inversion (SeMDI) of TEM data. SeMDI can be used additionally for inversion of DC data, and for joint inversion of TEM and DC data (www.aarhusgeo.com/Overview/products-overview.html).

These are the best known tools for TEM data inversion. The basic principles outlined during the work for the interface design and architecture of interpretation systems have been applied to new software for processing and interpretation of resistivity data. Analysis of the software revealed some trends in the progress of interpretation systems and allowed formulating requirements to the designed programs.

An important requirement for such a system, mentioned in many publications (e.g., Svetov and Ageev, 1999), is to account for fast-decaying induced polarization (IP). The IP effects were found out to be responsible for nonmonotonous behavior and even sign reversal of voltage-decay curves (transient or TEM responses) often reported since the early 1970s. For years, induced polarization has had many geological applications. The best studied is IP measurable by grounded electric lines, which has large relaxation times and thus allows neglecting eddy current induced by transmitter current change. The fast-decaying IP associated with inductive excitation and measuring of the transient process is commonly treated as geological noise, for two main reasons: (i) this kind of IP is poorly understood and (ii) eddy currents predominate at early times. Meanwhile, joint inversion (for loops of different configurations and/or sizes) with frequency-dependent conductivity allows estimating IP parameters even when eddy currents are rather strong (Kozhevnikov and Antonov, 2007, 2008, 2009a,b). Therefore, these requirements have been taken into account to update the earlier TEM inversion software (Antonov et al., 2010, 2011a; Kozhevnikov et al., 2012).

We are currently developing our own approaches and programs, including those to allow for fast-decaying IP effects. In 2005–2007, our team (E.Yu. Antonov and V.V. Potapov, IPGG, Novosibirsk) designed the *Delphi Inv_QQ_IP* program, one of the first software used for this purpose. It was applied successfully to TEM data from the Yakutian kimberlite province (Stognii and Korotkov, 2010). The results of that study and some later ones were taken for reference when designing the new TEM-IP software described below.

TEM-IP software: general characteristics

The TEM-IP software is a tool for various interpretation purposes, including forward modeling, single and/or joint inversion, as well as data import/export and visualization.

User interface. The home base is designed as a tabbed multidocument interface, each document seen in a separate floating window as an independent module. By default, the windows are displayed in a full-screen mode and are switched by selecting tabs in the top panel. The panel modules serve for visualizing and handling input and output program data. The system can run two types of documents and five types of panels. There are panels of menu, tools, and tabs at the home base top (Fig. 1); the progress bar in the bottom; the *Project* window panel on the left; and three other panels (*Graphics*, *Model*, and *Loop configuration*) which belong to the interpretation window on the right. The user can move the interface components within the home base to change its aspect.

The software version for research applications needs the options of data import and export in the formats used by different acquisition systems and/or by third-party software. Currently data import is possible for the formats of such systems as *SGS-TEM*, *FastSnap*, *Tsikl* (Russian for *Cycle*), TEM-FAST, and the potentiality can be further extended as far as needed.

The today's advanced acquisition systems collect ever larger amounts of data, which urges interface development for 2D and 3D visualization of voltage decay curves and their transformations (apparent resistivity $\rho_\tau(t)$ or conductance $S_\tau(H_\tau)$), as well as for export of data and inversion results in forms convenient for using in graphic programs according to the user's choice.

A graphic interface has been designed to edit data and run arithmetic operations, averaging, and inversion of transient responses. The system can convert transients to the frequency domain, which may be useful for on-fly analysis of their spectra and/or preparation of data for 2D or 3D inversion. The reason is that 2D and/or 3D modeling can be faster in the frequency domain, while independent solutions at selected bandwidths allow applying parallel computation.

The software is project-oriented, i.e., it can bring 1D or 2D primary EM data together into a project for further arrangement and fast access, and work separately with each object. For selected data, one can obtain resistivity sections (Fig. 2), and time sections of emf (voltage), apparent resistivity, and/or conductivity.

The system has its own internal format for saving field data, instrument specifications, and model parameters. The files have their titles that record the sounding index and loop configuration, acquisition information (recording time, voltage, measurement error), and model, which are used when saving the inversion protocol.

For this purpose, the program can preprocess and edit measured data (either in tabulated or graphic forms); it can create the history of earth models obtained by inversion and store them in a special *.mdstore file. There is also a file that stores the integral quadrature formulas for the Hankel transform to optimize forward modeling. A universal option has been designed for exporting profile data to the formats supported by the *Surfer* and *Voxler* (Golden Software) graphic systems.

Forward modeling. The software kernel consists of a forward solution for a TEM acquisition system laid upon the surface of a layered conductive polarizable earth. Then the forward models are fitted (optimized) within a specified space of parameters during inversion, and the forward algorithms

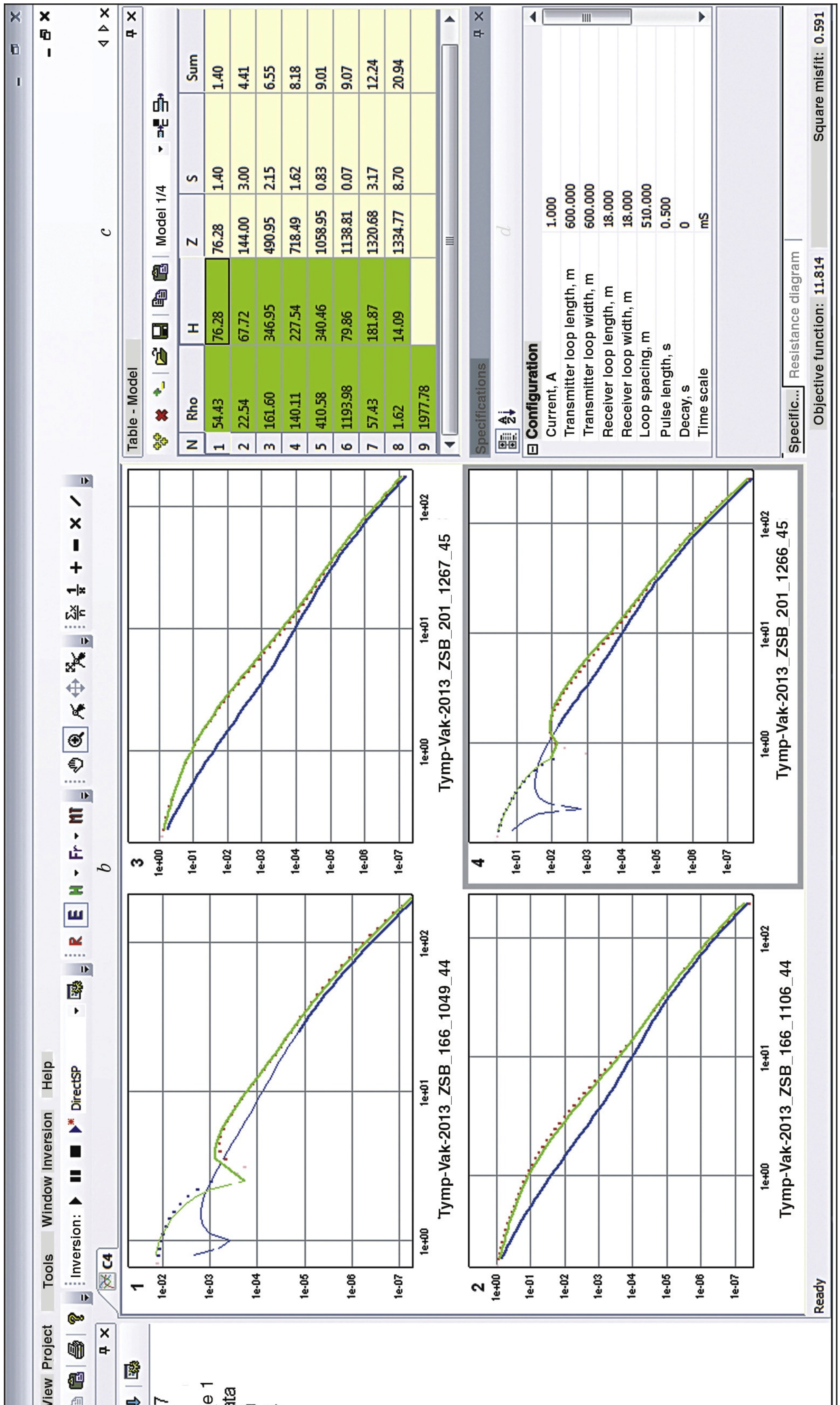

Fig. 1. TEM-IP main window. Panels: *Project* data (*a*); *Graphics* (*b*); *Model* tab (*c*); *Specifications* tab (*d*).

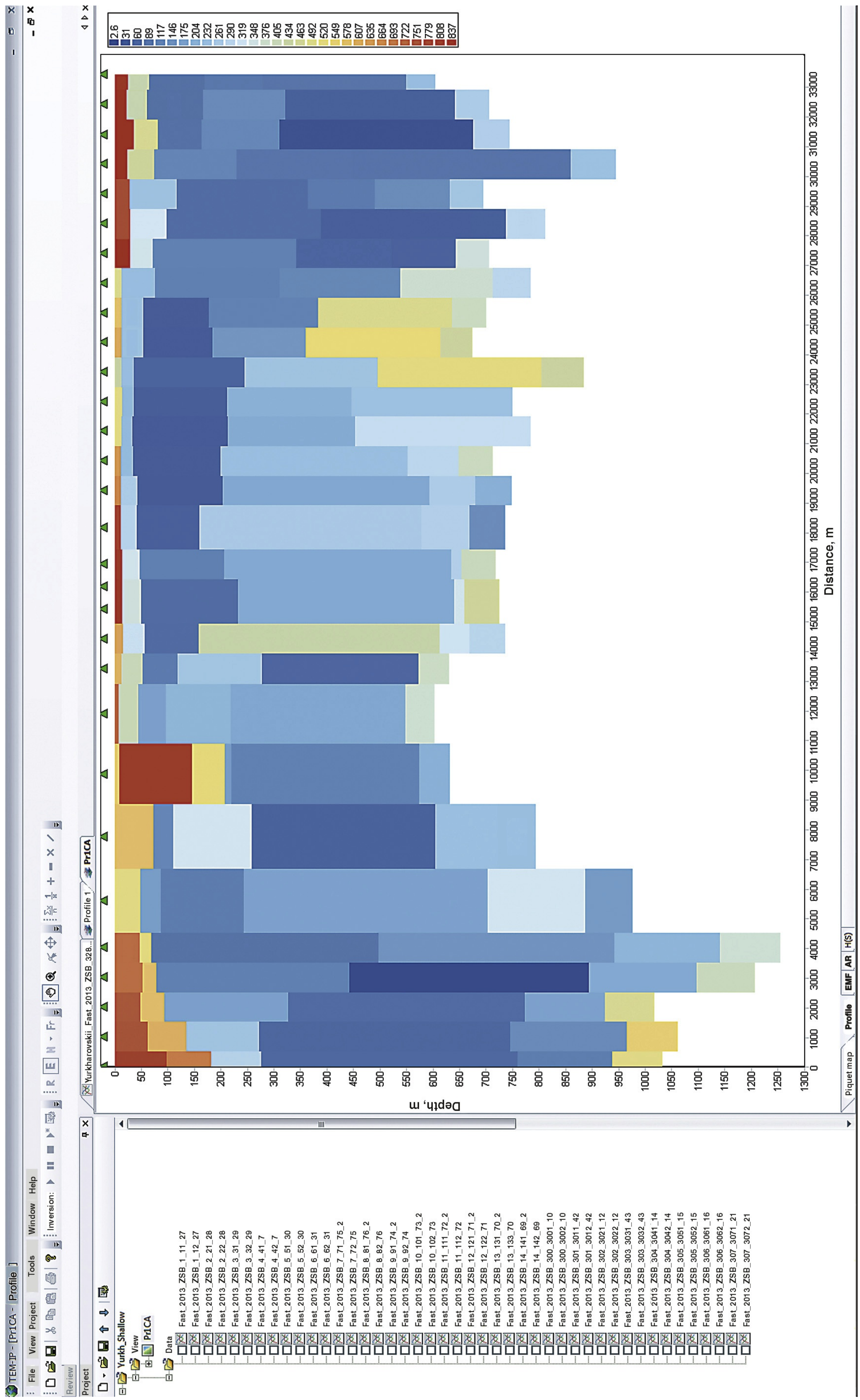

Fig. 2. Single inversion results presented as a geoelectric section.

thus have to be fast. The software has options of speeding up computation using various algorithmic approaches depending on problem formulation ("normal" or polarizable earth); selecting the set of forward routines and varying computation speed and accuracy, with a possibility of switching from one routine to another; running parallel algorithms.

The current software version uses two forward codes. A fast algorithm for computing the eddy current field with thin-film (S films) approximation of the layered earth in the case of a nonpolarizable earth (Tabarovsky and Epov, 1990), and a Fourier solution for IP-affected data. The latter solution is provided by several algorithms: computing the fundamental function of the layered-earth problem; integration over the spatial frequency (Hankel transform); frequency-to-time domain sine and cosine Fourier transforms (Tabarovsky, 1979; Tabarovsky and Sokolov, 1982). For solutions in the case of a layered polarizable earth see (Epov and Antonov, 1999, 2000). Forward problems for loop-loop and loop-line data are solved using the Unv_QQ and QLineIP modules (Kozhevnikov and Antonov, 2007, 2009a,b, 2008). The Fourier forward algorithm includes several resource-intensive cycles (up to 99.5% computing time) run in parallel to accelerate the computation almost proportionally to the number of the processors (Fig. 3). The algorithm was tested on multicore PCs, as well as on multiprocessor clusters of the type of NCS-160, NCS-30T (www2.sscc.ru).

Forward modeling with the Cole–Cole complex frequency-dependent conductivity accounts for the effects of fast-decaying IP. The Cole–Cole equation (Cole and Cole, 1941), the most popular frequency representation for IP-affected data, for complex conductivity is (Lee, 1981):

$$\sigma^*(\omega) = \sigma_0 \frac{1 + (i\,\omega\,\tau)^c}{1 + (1 - \eta)\,(i\,\omega\,\tau)^c},$$

where $i = \sqrt{-1}$, σ_0 is the dc conductivity (S/m); η is the chargeability ($0 \le \eta \le 1$), τ is the relaxation time (s); c is the exponent ($0 < c \le 1$). Thus, the model of an n-layer conducting polarizable earth is fully described by the vector

$$\mathbf{M} = (\rho_1, \ldots, \rho_n, h_1, \ldots, h_{n-1}, \eta_1, \ldots, \eta_n, \tau_1, \ldots, \tau_n, c_1, \ldots, c_n).$$

The inverse solution is commonly sought either for a complete set of model parameters $\mathbf{M}$, or for some of its subsets $\mathbf{P} \subseteq \mathbf{M}$.

Inversion consists in fitting the computed model to observations and search for a model providing the minimum misfit of parameters (minimizing the misfit functional). According to the user's choice, this may be either weighted relative (1) or weighted square (2) misfit between observed and computed data:

$$\Phi_1(\mathbf{P}, N) = \frac{1}{N}\sum_{i=1} \left| \frac{f^e(t_i) - f^t(\mathbf{P}, t_i)}{\delta(t_i) f^e(t_i)} \right|; \qquad (1)$$

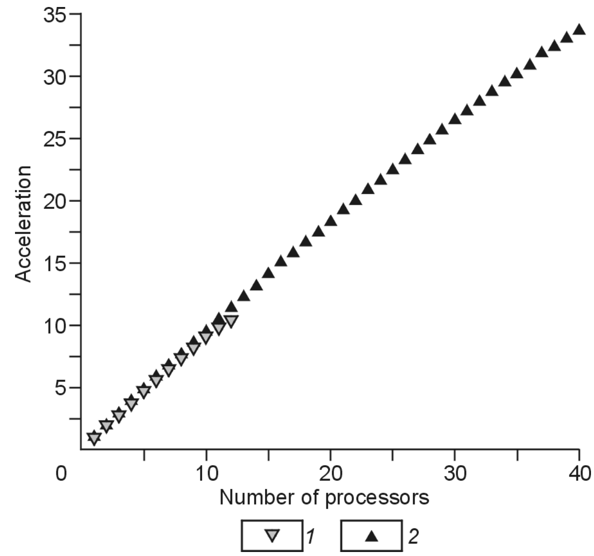

Fig. 3. Acceleration of computing (ratio of computation time t_p with p processors to that with one processor (t_1)) vs. number of processors: *1*, NCS-160; *2*, NCS-30T.

$$\Phi_2(\mathbf{P}, N) = \left(\frac{1}{N-1}\sum_{i=1} \left(\frac{f^e(t_i) - f^t(\mathbf{P}, t_i)}{\delta(t_i) f^e(t_i)} \right)^2 \right)^{1/2}, \qquad (2)$$

where $\mathbf{P}$ is the vector from the space of model parameters, $\{t_i, i = 1, \ldots,\}$ are the measurement times, $f^e(t)$ are experimental data, $f^t(\mathbf{P}, t)$ is the model response, δ is the relative measurement error.

In joint inversion, it is a more complicated functional (3), a weighted sum of (1) or (2) which includes data from several measurement systems, for which a single model is sought:

$$\Phi_3(\mathbf{P}, N) = \sum_{\alpha=1}^{L} \beta_\alpha \Phi_\alpha(\mathbf{P}, N_\alpha), \quad N = \sum_{\alpha=1}^{L} N_\alpha, \quad \sum_{\alpha=1}^{L} \beta_\alpha = 1, \qquad (3)$$

where L is the number of TEM loop arrays; Φ_α is the functional of the form (1) or (2) for an array indexed as α; β_α are the weight coefficients that allow the user to manage the contributions from individual measurements according to their amount and quality or with regard to a priori information. Minimization is run by fitting the $\mathbf{P}$ model parameters or with a modified method of Nelder and Mead (1965).

The interpretation process is complicated and often multistage. Several inversion runs with different starting models may be needed sometimes for a nonpolarizable earth and almost always in the case of a polarizable earth. First the model data (resistivity and layer thicknesses) are put in, along with the loop configuration parameters (transmitter and receiver loop sizes), operation conditions (transmitter current, measurement time range, and transient or current decay time), as well as such inversion parameters as the objective function minimum, number of iterations, etc. The inversion procedure implies fitting of earth's physical parameters, forward calculations, viewing measured and computed voltage decay or apparent resistivity curves. The current results of the iterative

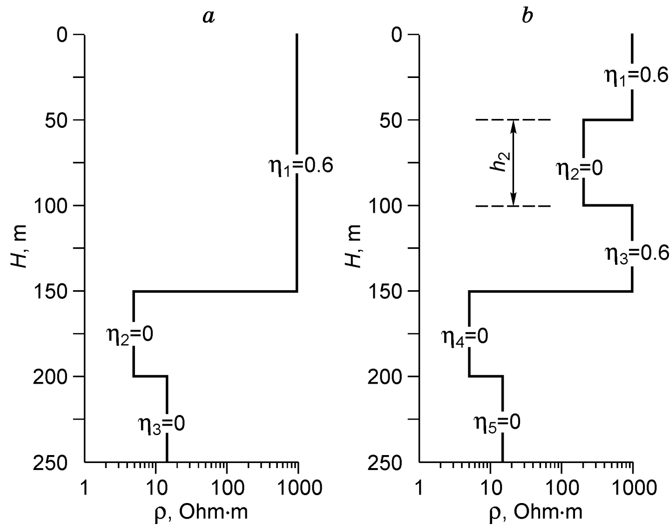

Fig. 4. Resistivity-depth profiles: *a*, Reference model (without talik); *b*, with a talik in the upper section part.

process are displayed in the screen for interactive management by the user.

Examples of using the TEM-IP software

Below we cite examples of applying TEM-IP to two cases of single and joint inversion of TEM responses with effects of fast-decaying IP.

Search for taliks in the Pyakyakhinka oilfield. Lenses of water-saturated unfrozen rocks (taliks) in permafrost are often the only water source in high-latitude regions (Kozhevnikov et al., 2012). Taliks form underneath rivers and lakes and, being more conductive than frozen ground, are well pronounced in DC-derived regional resistivity sections obtained in the course of permafrost or structural studies. Therefore, DC resistivity surveys, and especially multioffset profiling, play the leading role in their detection and investigation (Ogilvi, 1990). The method is workable if unfrozen rocks lie at relatively shallow depths, but measurements in frozen shallow ground may be problematic because a galvanic contact of electrodes with the earth is required.

In this respect, the TEM method may be an advantageous tool for detection of taliks: it can go without grounding, is sensitive to conductors lying under resistive rocks, and provides high resolution.

TEM soundings were applied to detect taliks in the Pyakyakhinka oilfield for the purposes of water supply. The TEM data from the Pyakyakhinka oilfield area were inverted with the TEM-IP software (Antonov et al., 2010) which is designed for forward modeling and inversion of responses from a conducting polarizable layered earth and can account for fast-decaying IP effects appearing as monotony failure or sign reversal of voltage decay curves. The acquisition was in March and April 2011, by A.K. Zakharkin, with the *Tsikl*-7 system (ZaVeT-GEO, Novosibirsk) along two profiles. The profiles ran in the river and lake environments, one along the Indikiyakha River and the other across Ngarkato Lake. Most of measurements were at every 100 m, with a loop-loop configuration: a 35×35 m transmitter loop and a receiver of an effective area of 400 or 2500 m^2 laid 45 m far from the transmitter center.

The production soundings were preceded by six test soundings in a watershed area known to be devoid of taliks. In the tests, transient responses were generated and measured by a central-loop system with a receiver placed at the center of a 35×35 m transmitter.

Inversion of transients affected by fast-decaying IP provided an idea of the resistivity pattern in the watershed area. The chosen starting model consisted of three layers with the polarizable top layer (Fig. 4*a*) of $\rho_1 = 10^3$ Ohm·m, $\eta_1 = 0.6$, and $\tau_1 = 150$ μs, $c_1 = 1$, the parameters typical of frozen sediments, most likely coarse-grained rocks like sand, judging by large ρ_1. The intermediate layer, 50 m thick on average, was low resistive (a few Ohm·m) and had a conductance about 10 S. It may be clay, where pore water never freezes even at negative temperatures. The base layer likewise had a low resistivity of 15 Ohm·m and may consist of clay as well. A three-layer model with these parameters (Fig. 4*a*) can be used for reference in modeling effects from a talik in the top layer.

As a talik appears in the upper part of the section, the three-layer model becomes a five-layer one (Fig. 4*b*), with a relatively low-resistive ($\rho_2 = 200$ Ohm·m) and nonpolarizable talik of the thickness h_2 (Fig. 4*a*). However, as shown by special modeling, the effect of the talik on the transients is insufficient for reliable constraining its parameters as a separate layer. Nevertheless, incorporating a talik into a three-layer model causes significant changes to effective or equivalent parameters of the top layer (which actually includes three sublayers). Namely, the presence of a nonpolarizable talik, more conductive than the host frozen rocks, may be expected to reduce the total conductivity and chargeability of the composite upper layer. Therefore, the transients collected along the river and lake profiles were inverted assuming a three-layer earth with a polarizable upper layer (Fig. 4*a*).

The inversion results for the lake area are shown in Fig. 5 as variations of parameters along the profile. In spite of notable local features in the parameters of the upper layer, the curves represent regional-scale patterns of parameter variations with distance (Fig. 5). The thickness h_1 of the top layer varies from 72 m to 270 m, being the largest in the northern flank (point 260–280). The resistivity ρ_1 ranges from 43 Ohm·m in the profile center to 4300 Ohm·m on the ends, the difference being three orders of magnitude. The chargeability η_1 is 0.12–0.78, the lowest and the highest values likewise being for the profile center and flanks, respectively. The time constant τ_1 is in the range from 35–290 μs, 80 μs on average, with τ_1 generally higher in the southern flank of the profile than in the northern one, and without local anomalies. The Cole-Cole exponent remains $c_1 = 1$ in all cases.

The parameters of the top layer obtained by inversion have values typical of frozen sedimentary rocks (Kozhevnikov and Antonov, 2006). The 2 km long central part of the profile

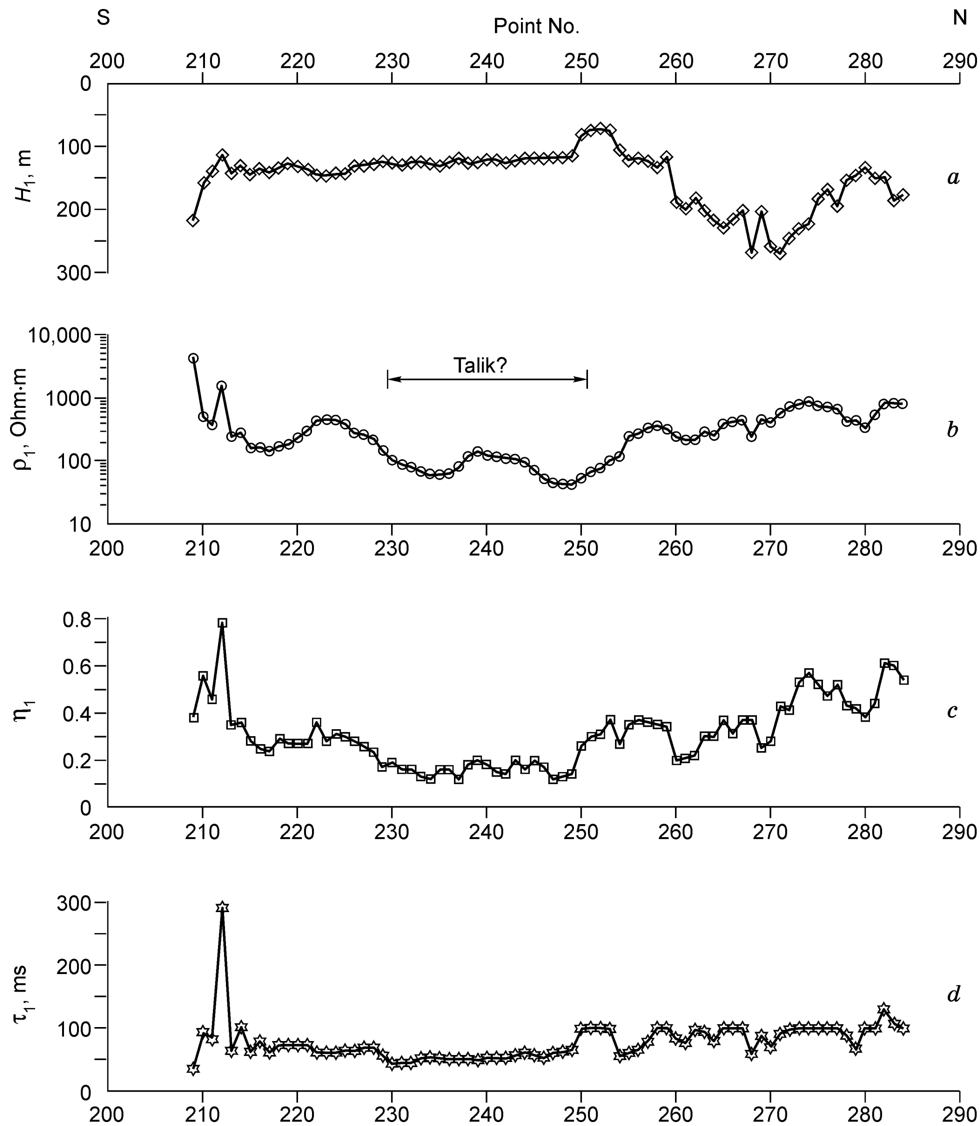

Fig. 5. Thickness h_1 (*a*), resistivity ρ_1 (*b*), chargeability η_1 (*c*) and relaxation time τ_1 (*d*) of the upper layer along the lake profile. Sounding points are spaced at 100 m. Line with arrows marks the zone of low resistivity and chargeability.

between points 230 and 250, with the lowest resistivity ρ_1 chargeability η_1, appears to be the most promising in terms of taliks location. Therefore, an elongate lens of unfrozen rocks (a talik) may exist there to a high probability.

Oil exploration in East Siberia. Another example illustrates how the program can run joint inversion of IP-affected TEM responses collected during oil exploration in East Siberia. The TEM method has been used since the early 1970s in East Siberia, but fast-decaying IP effects have never been recorded unlike the neighbor area of western Yakutia. One cause may lie in central-loop acquisition with large transmitter loops (0.5–1 km or more) poorly sensitive to the effects much weaker than eddy current. Lately however fast-decaying IP is becoming better resolved due to advanced combined configurations (Antonov et al., 2011b; Kozhevnikov and Kompaniets, 2010; Kompaniets et al., 2013) of one central-loop and four loop–loop systems at each point (Fig. 6*a*), with a 500×500 m transmitter at zero offset (central-loop system) and loop spacing of 500 and 1000 m in the loop-loop system.

The resistivity pattern in southern East Siberia can be approximated by a 1D layered model without azimuthal anisotropy. If the rocks are conducting but non-polarizable, the transients measured by the central-loop and loop-loop systems differ at early times but coincide at late times. The single and joint inversion procedures give the same model result, as one can see in apparent resistivity ρ_τ curves in Fig. 6*b*, measured within the Zaslavsky license area (Angara–Lena plateau, southwestern Irkutsk region). A different pattern was observed in the Central Oka license area west of Zaslavsky (Fig. 6*c*): the loop–loop ρ_τ curves merge at late times. Unlike the previous case, however, the right-hand branch of the central-loop ρ_τ curve lies above that for the loop-loop response. Inversion of loop-loop transients gives the same model, without regard to polarization, but it differs

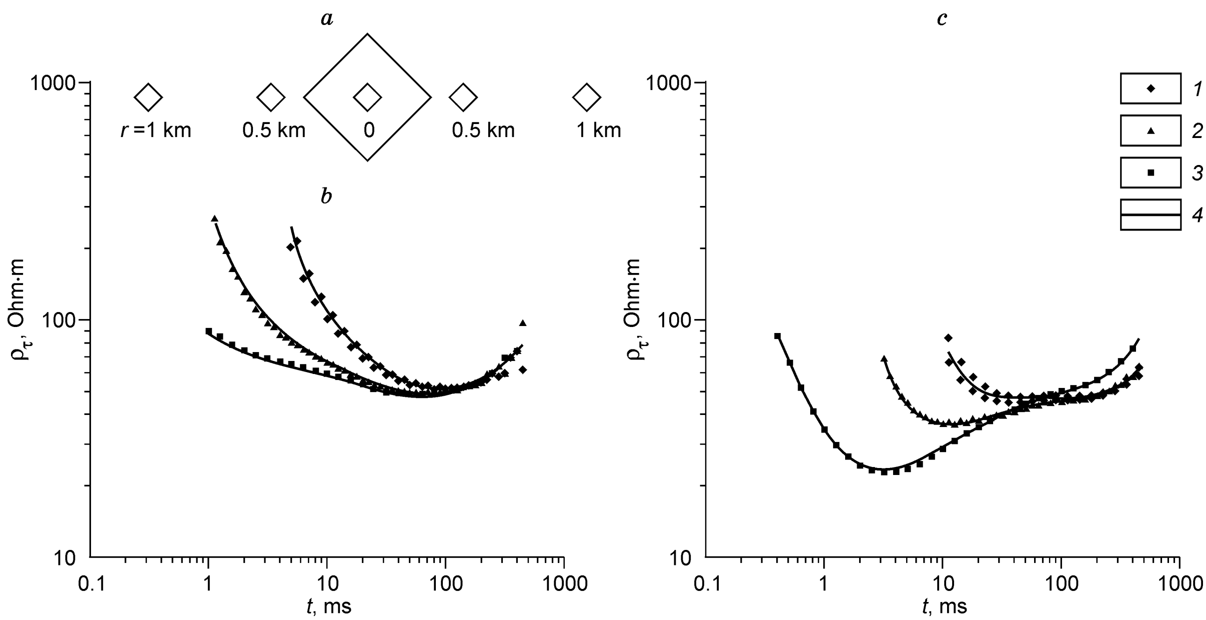

Fig. 6. A TEM system (*a*); ρ_τ curves measured at Zaslavsky (*b*) and Central Oka (*c*) sites. *1–3*, field data: *1*, offset 1 km; *2*, offset 0.5 km; *3*, central-loop configuration; *4*, model curve.

strongly from the pattern resulting from inversion of central-loop responses; in this case, joint inversion of data acquired by all five systems fails. The effects of fast-decaying IP have been observed in 85% of the totally 200 sounding points.

TEM-IP joint inversion allowed bringing together the central-loop and loop-loop responses with a single reference model. Generally, the obtained resistivity model fits the sedimentary section of the southern Siberian craton, with a 50–80 m thick low-resistive (ρ = 10–15 Ohm·m) polarizable upper layer (η = 3–4%), τ = 50–60 ms, and $c \approx 0.5$. The layer consists of up to 60 m thick Jurassic carboniferous sediments bearing graphite and pyrite. Induced polarization in the Central Oka area decays about 1000 times slower than that in Yakutia, while the relaxation times vary in a broad range.

Conclusions

The reported TEM-IP software has been designed for inversion of transient responses affected by fast-decaying IP. Data interpretation is performed with a special stepwise technique. The new software and the methods have been efficient in detection of taliks in the Pyakyakhinka oilfiled and in petroleum exploration in the southern Siberian craton.

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