DOI: 10.18454/PMI.2017.2.178

UDC 550.837

FREQUENCY ELECTROMAGNETIC SOUNDING WITH INDUSTRIAL POWER LINES ON KARELIA-KOLA GEOTRAVERSE

Aleksandr N.SHEVTSOV[1], **Abdulkhai A.ZHAMALETDINOV**[1], **Vitalii V.KOLOBOV**[2], **Maksim B.BARANNIK**[2]
[1] *Geological Institute of the Kola Science Centre of the RAS, Apatity, Russia*
[2] *Centre for Physical and Technological Problems of Energy in Northern Areas of the Kola Science Centre of the RAS, Apatity, Russia*

The paper describes theory, method and first experimental results of research on the interaction between electromagnetic waves of extremely low and ultra low frequency (0.1-200 Hz), the Earth crust and ionosphere in the field of two mutually orthogonal industrial power lines, 109 and 120 km long, in the course of FENICS experiment (Fennoscandian Electrical conductivity from Natural and Induction Control Source soundings). The main focus was on the observation results along the line of Karelia-Kola geotraverse over a distance of 700 km from the source. High horizontal homogeneity of geoelectrical lithosphere section has been detected in the eastern part of the Baltic shield at depth range from 10-15 to 50-70 km. Parameters of «regular» lithosphere section have been specified to the depth of 60-70 km. As a result of inverse problem solution for the western part of Karelia and Central Finland, a zone of decreased transverse resistivity has been detected at the depth of 50-60 km, corresponding to the area, detected by seismic methods, where Moho boundary reaches the same depth.
***Key words*:** electromagnetism, deep sounding, controlled sources, industrial power lines, electrical resistivity, interpretation

***How to cite this article*:** Shevtsov A.N., Zhamaletdinov A.A., Kolobov V.V., Barannik M.B. Frequency Electromagnetic Sounding with Industrial Power Lines on Karelia-Kola Geotraverse. Zapiski Gornogo instituta. 2017. Vol. 224. P. 178-188. DOI: 10.18454/PMI.2017.2.178

Introduction. Absence of conducting sedimentary cover creates favorable conditions for deep electromagnetic sounding of the lithosphere on the territory of Fennoscandian Shield. The first deep soundings were carried out using controlled sources [8]. Starting from mid-1960s, deep soundings of Fennoscandian Shield were carried out using predominantly magnetotelluric method (MT), due to its greater propagation distance and lower costs as compared to other methods. In the early 1970s there was a revive of interest in electromagnetic tests with controlled sources because of a large-scale deep sounding experiment «Khibiny», using a 80 MW magnetic hydrodynamic generator [6, 16]. Later, in the early 1990s, several deep sounding experiments were carried out using a 2 MW ultra low frequency antenna «Zevs» [9]. Abovementioned tests permitted to obtain new information on deep electrical section of the Earth crust and structure of crustal conductivity anomalies. The disadvantage of these and all other (performed throughout the world) deep sounding experiments with controlled sources is application of only one single polarization of the primary field.

This work is the first attempt to close this gap by way of performing deep sounding with two mutually orthogonal power lines, 109 and 120 km long, acting as antennas of different polarization. All the observations have been carried out over the distance of 856 km from the source. Their results enabled to carry out deep sounding in a wide-range wave zone of low frequencies (0.1-200 Hz) and to reach greater depths of sounding (50-70 km) under conditions of low conductivity crystalline basement. The experiment went under the codename FENICS (Fennoscandian Electrical conductivity from Natural and Induction Control Source soundings). The first soundings of FENICS series were performed in 2007 and 2009 [5, 6]. This paper describes theoretical principles, methods and results of interpretation based on previous data, as well as new results of FENICS experiment, obtained in 2014.

Research methods. Principle diagram of the FENICS experiment is presented in Fig.1. Transmitting generator «Energy-2» with capacity 200 kW [2, 3] is interchangeably connected to two mutually orthogonal industrial power lines, where it creates alternating current in the frequency range of 0.1-200 Hz. Such assembly allows to «transilluminate» deep structure of the lithosphere using two mutually orthogonal polarizations of the primary field. FENICS-2014 experiment was carried out in two stages. At the first stage (from 23rd to 30th August 2014) the current was applied to the latitudinal line L1; at the second stage (from 1st to 8th September 2014) – to the meridian line

DOI: 10.18454/PMI.2017.2.178

L2. At both stages of the experiment all operations were carried out at night, from 01:00 to 05:00 Moscow time. For the majority of sounding stations, electrical properties of the upper section have been studied by means of direct current sounding with spacing from 2 to 15 km.

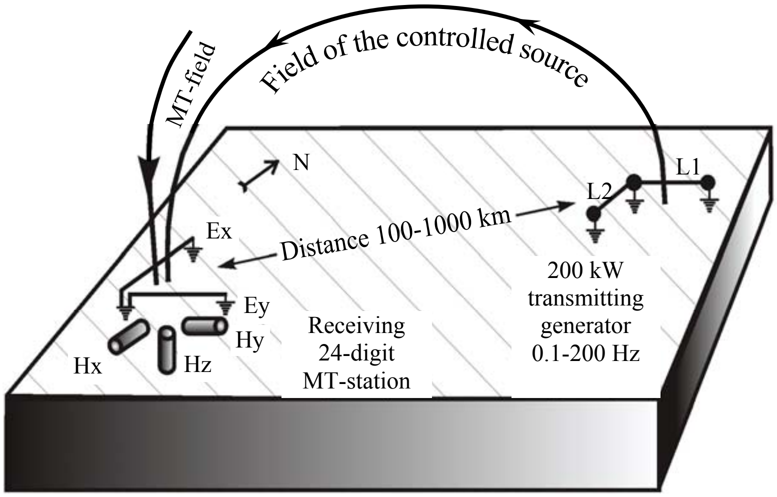

Fig.1. Diagram of frequency electromagnetic sounding using two mutually orthogonal sources

A schematic connection diagram of extremely-ultra low frequency (ELF-ULF) generator «Energy-2», used in the FENICS experiment, is presented in Fig.2. Generator «Energy-2» with the maximum output capacity 200 kW has been specially designed for the FENICS experiment [7]. The power for the generator comes from a three-phase auxiliary transformer of the substation 1, with output voltage 380 V and capacity over 200 kW. Input alternating voltage is increased and rectified by a power converter (PC) 2. Output voltage from the PC equals 1100 V. High-voltage inverter (HVI) 3 creates sinusoidal current of the required frequency and amplitude in the loading (antenna), using method of pulse width modulation. Depending on the task, the waveform of the current can be sinusoidal, triangular or meander. Maximum amplitude of voltage in HVI output reaches 1100 V. Low frequency filter (LFF) 4 suppresses high-frequency interference, associated with pulse width modulation. Matching unit (MU) 6 is used to compensate inductance of the power line at frequencies above 5 Hz by means of series capacities. Overvoltage protection circuit (OPC) 7 protects HVI output from external overvoltage (e.g., from lightning strikes).

First output terminal of the generator (*A* in Fig.2) is connected to the grounding of the basic substation, where the generator «Energy-2» is located. The second terminal is connected to three conjugated phase conductors of the aerial line. The current passes along the power line and returns through the grounding of substation (*B* in Fig.2) and through the ground. The length of transmitting antennas – power lines – is 109 km for line L1 and 120 km for line L2.

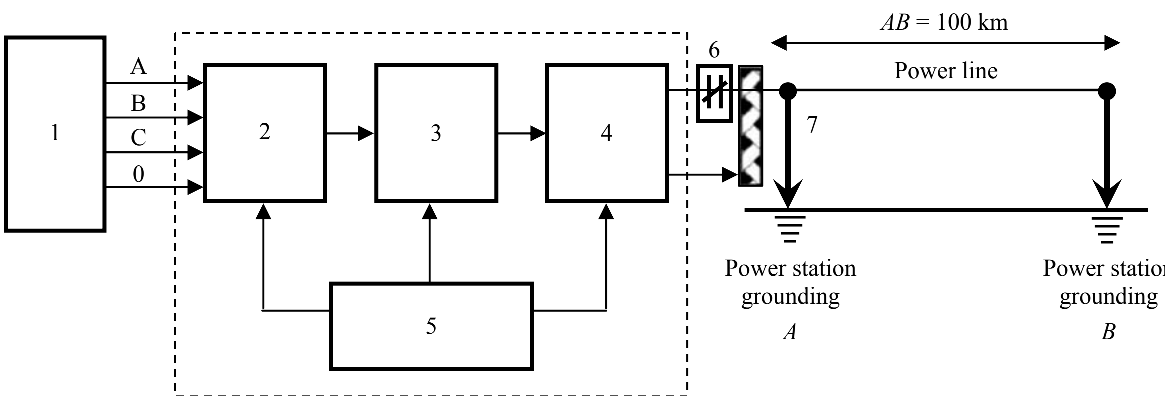

Fig.2. Schematic connection of the generator «Energy-2» to the industrial power line *AB*

1 – three-phase auxiliary transformer of the 380 V substation; 2 – AC-DC converter; 3 – high-voltage inverter; 4 – low frequency filter; 5 – system of control, regulation, protection and automation; 6 – matching unit; 7 – overvoltage protection system

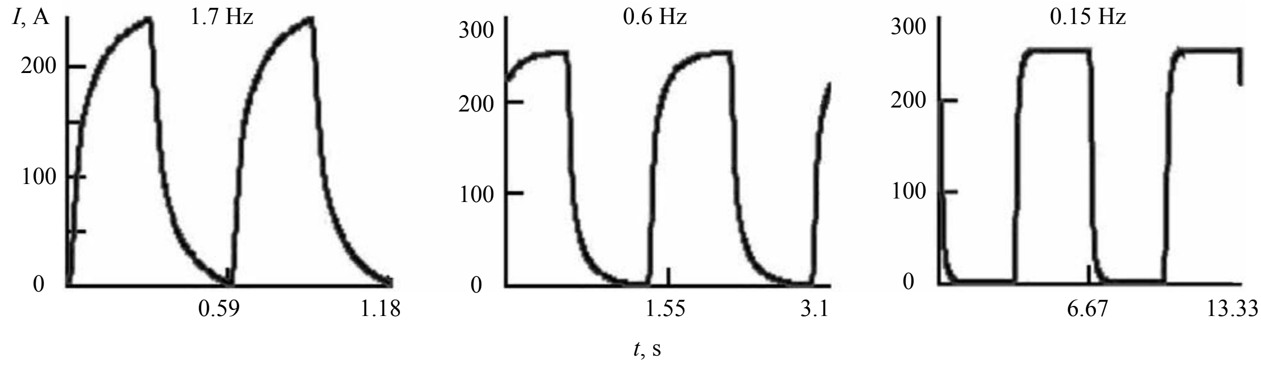

Fig.3. Shapes of low frequency signals on the example of current recording on line L1

When performing frequency sounding with long grounded power lines, the following parameters should be taken into account: individual conductor resistance («internal» inductive resistance); actual configuration of the current-carrying conductor, which is not always straight-line; alteration of current intensity (amplitude) along the power line depending on frequency; resistance of the reverse current, flowing in the lower semi-space («external» inductive resistance).

On the latitudinal line L1 (see Fig.1), the current of first harmonic varied within limits of 170-235 A at low frequencies (0.1-10 Hz) and within limits of 25-60 A at high frequencies (100-200 Hz). The second power line L2 (Kola-Monchegorsk) has a meridian direction (north-south) and the length of 120 km. Overall direct current resistance on the power line L2 amounts to 6 Ohm, which is double the resistance of line L1 (2.5 Ohm). As a result, L2 current has different characteristics: it varies across the interval of 100-120 A at low frequencies (0.1-10 Hz) and reaches 40-80 A at high frequencies (100-200 Hz). At frequencies over 5-10 Hz inductive resistance of both power lines has been compensated by means of capacitive matching unit (Fig.2, pos.6). The current in transmitting antennas has been recorded on a personal computer using analog-to-digital converter E140 with sampling frequency 5 kHz. The current shape in transmitting line was changing from sinusoidal at high frequencies to triangular, trapezoidal and meander at low frequencies (Fig.3). Frequency stability has been maintained at the level not lower than 10^{-7} Hz. Current in transmitting antennas and signals in receiving stations have been synchronized using global positioning system (GPS) with an error less than 1 ms.

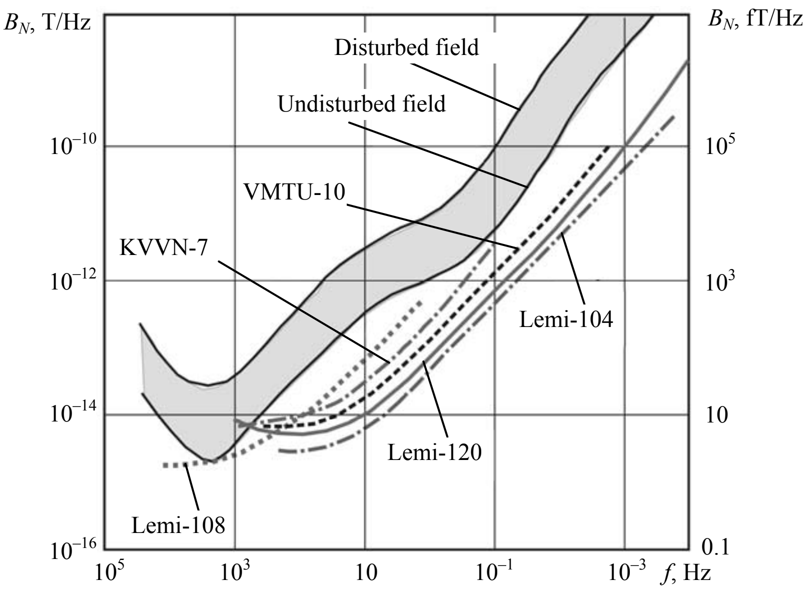

Fig.4. Spectral density of self-noise amplitude B_N depending on frequency f for induction sensors, used in FENICS experiment (VMTU-10 and KVVN-7), as compared to Lemi sensors

Receiving stations. Signals have been recorded with the help of wide-band five-component 24-digit magnetotelluric and audiomagnetotellurics (MT-AMT) digital stations. Harmonic signals from the controlled source have been filtered from MT-AMT variations using fast Fourier transformer (FFT-procedure).

A key quality parameter of MT-stations is self-noise level of magnetic sensors. In Fig.4 a cu-

 DOI: 10.18454/PMI.2017.2.178

mulative diagram is presented, which demonstrates spectral self-noise characteristics of magnetic sensors, used in FENICS experiment (VMTU-10 and KVVN-7), as compared to a widely recognized brand Lemi (Lviv, Ukraine). A grey band represents frequency characteristic of noises created by natural variations of MT-AMT field.

The quality of inductive sensor is primarily defined by the position of its noise characteristic compared to the average frequency characteristic of natural noises (grey band in Fig.4). If self-noises of the sensor are lower than natural noises, it demonstrates high quality of the sensor. Such sensor can register amplitude and variation phase of the natural field with great reliability and at the same time perform the task of electromagnetic sounding in the field of controlled sources. Currently the propagation distances of sounding research with natural and controlled sources tend to get closer and even to overlap. It happens due to application of precision inductive sensors in a wide range of frequencies (from 10^{-3} to 10^{3} Hz) and opportunities of analog-to-digital conversion of recordings in a wide dynamic range (24 digits and more). This trend opens up new possibilities for combined sounding using both natural and controlled sources. FENICS experiment is an attempt to move in this direction. It can be seen from Fig.4 that used measuring stations (VMTU-10 and KVVN-7) have spectral characteristics close to the best analogues of Lemi brand, which stands for a high standard in the modern equipment for MT-AMT research [18].

Data processing. Processing of primary data has been carried out by way of calculating ratios of spectral densities for auto- and cross-correlating functions of stationary stochastic processes using Wiener-Khinchin theorem [17], which establishes links between auto-correlating function $R_{xx}(\tau)$ of the stochastic process *x,* depending on the time shift τ, and cross-correlating function $R_{xy}(\tau)$ of two stochastic processes – *x* and *y* with respective spectral densities $S_{xx}(\omega)$, $S_{xy}(\omega)$, depending on circular frequency ω, by way of direct and inverse Fourier transform:

$$S_{xx}(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}R_{xx}(\tau)\exp(-i\omega\tau)d\tau\,;$$

$$S_{xy}(\omega)=\frac{1}{2\pi}\int_{-\infty}^{\infty}R_{xy}(\tau)\exp(-i\omega\tau)d\tau\,,$$

where $R_{xx}(\tau)=\int_{-\infty}^{\infty}S_{xx}(\omega)\exp(i\omega\tau)d\omega$; $R_{xy}(\tau)=\int_{-\infty}^{\infty}S_{xy}(\omega)\exp(i\omega\tau)d\omega$.

Amplitudes of field components have been estimated using maximum values of auto-correlating function of these components at the frequency of current generator in the source. Basing on spectral plane phase of the cross-correlating function of the respective field components, phase shift between these components has been defined. Moreover, amplitude-frequency and phase-frequency characteristics of sensors have been taken into account, as well as azimuth of magnetic inclination, length of measuring lines etc. Measured field has been translated into rectangular coordinate system – axis *X* in north-south direction, axis *Y* – east-west direction, axis *Z* – vertical line. Then spectral analysis has been performed, as well as assessment of auto-correlating spectral density of each component's capacity and cross-correlating spectral densities of capacities for associated and anti-associated couples of estimated field components. Spectral analysis has been carried out using Welch method with Blackman-Harris sliding window, based on FFT [19]. Overlapping varied from 20 to 50 % depending on window width and length of time series.

Spectral processing of electrical *Ex*, *Ey* and magnetic *Hx*, *Hy* field components has been performed over the distance 752 km from circuit line L1. Its results are presented as a diagram of spectral density capacity of controlled source signals for registered components of the electromagnetic field (Fig.5). The signals are clearly seen only on the main, associated field components – latitu-

 DOI: 10.18454/PMI.2017.2.178

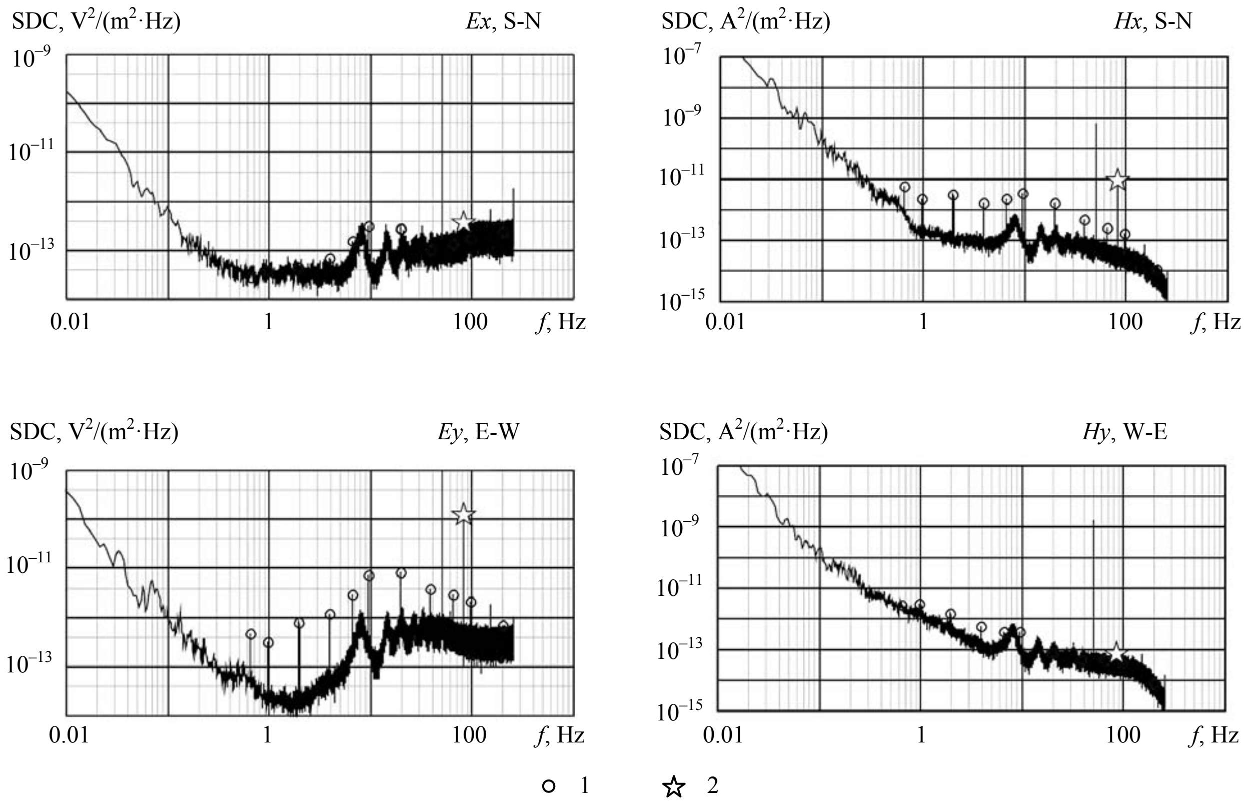

Fig.5. Diagrams of spectral density capacity (SDC) of signals basing on FENICS-2014 experiment data, point 7v, r = 752 m

1 – signals from power line L-1; 2 – signals from ELF-antenna «Zevs»

dinal component of electrical field *Ey* (parallel to L1) and meridian magnetic component *Hx* (orthogonal to L1).

Analysis of SDC diagrams (Fig.5) gives a general overview of a deep geoelectrical section. Apparent increase in intensity of electrical and magnetic field components in the average range of 2-20 Hz under constant amplitude of the current (around 100 A) shows that resistance in the middle part of the lithosphere rises with depth and then decreases, i.e. the section belongs to type «K». In all the graphs the first harmonic of Schumann resonance (7.5 Hz) and higher harmonics up to 4th one are clearly seen. At the frequency 82 Hz in the associated components *Hx* и *Ey* (marked as stars in Fig.5) SDC maximums can be observed, which are created by the field of ELF-antenna «Zevs» [9], situated in the proximity of power line L1 and having the same sub-latitudinal orientation. At the frequency 50 Hz (and in odd harmonics) all four components have sharp maximums created by industrial noise.

At the next processing stage apparent electrical resistivity has been calculated for separate components of the field:

$$\rho_{Ex,y} = k_{Ex,y}\left(\frac{Ex,y}{I}\right);\ \rho_{Hx,y} = \omega\mu_0\left[k_{Hx,y}\left(\frac{Hx,y}{I}\right)\right]^2;\ \rho_{Hz} = \omega\mu_0 k_{Hz}\frac{Hz}{I},$$

where $\mu_0 = 4\pi\cdot 10^{-7}$ H/m – electrodynamic constant; $k_{Ex,y}$, $k_{Hx,y}$, k_{Hz} – geometrical coefficients for electrical and magnetic components of the field.

Values of geometrical coefficients for dipole approximation have been set equal to inverse values of corresponding components of the normal field in quasi-stationary approximation over homogenous semi-space with electrical resistivity of 1, under current intensity of 1 A [1]:

DOI: 10.18454/PMI.2017.2.178

$$\left.\begin{aligned} k_{Ex} &= \frac{2\pi r^3}{AB(3\cos^2\theta - 2)}; \quad k_{Ey} = \frac{2\pi r^3}{3AB\sin\theta\cos\theta};\\ k_{Hx} &= \frac{2\pi r^3}{3AB\sin\theta\cos\theta}; \quad k_{Hy} = \frac{2\pi r^3}{AB(1-3\sin^2\theta)};\\ k_{Hz} &= \frac{2\pi r^4}{3AB\sin\theta}, \end{aligned}\right\}$$

where r – distance between the center of the power line and the point of field observation, m; AB – length of power line, m; θ – angle between the axis of current dipole and observation point direction from the center of power line.

Apart from that, apparent resistivities ρ_{Zxy} and ρ_{Zyx} have been calculated for the components of input impedance Zxy and Zyx, where $Zxy = Ex/Hy$; $Zyx = -Ey/Hx$; $\rho_{Zxy} = (\omega\mu_o)^{-1}|Zxy|^2$; $\rho_{Zyx} = (\omega\mu_o)^{-1}|Zyx|^2$.

Geological and geographical interpretation. The observation profile of Karelia geotraverse 1a-6a (Fig.6, *c*) passes through the central part of Karelia megablock, least of all faulted with horizontal heterogeneities and least of all subject to industrial noise. Curves of apparent resistivity for the profile are presented in Fig.6, *a, b*. Observation points are located along the line at an average distance of 100 km from each other.

The basic information about the deep section has been obtained as a result of low frequency sounding in the range 0.1-200 Hz. Along with these, high frequency data were used, which have been retrieved by converting results of direct current sounding into high frequency area.

Analysis of apparent resistivity curves in Fig.6, *a* allows to identify their conformal character, pointing at common dependence between rock resistivity and depth all along the 700 km profile. Particularly, all the curves contain a decrease of resistivity in the area of 100 Hz, associated with heterogeneous conducting transitional zone, presumably of dilatant-diffusive (DD) origin. Under formal 1D interpretation, this zone manifests itself as conducting layers (Fig.7) at depths from 2-3 to 5-10 km; the authors have given it a name «DD layer» [12]. All the deep sounding curves contain a wide maximum in the area of 5-10 Hz with apparent resistivity values varying in the range from 30 to 100 thousand Ohm-meters.

The inverse problem has been solved basing on apparent resistivity curves, calculated using input impedance, for response function *Zyx* [14]. 1D sections, obtained as the result of inversion, are presented in Fig.7, *a*.

Bimodal inversion using both polarizations (from lines L1 and L2) has been carried out in three points (2a, 4a, 5a), where signals from both power lines have been measured. Matching results of inversion for two mutually orthogonal polarizations of the primary field are an argument for homogenous (one-dimensionality) model of deep electroconductivity of the lithosphere in the eastern part of the Baltic shield and, consequently, a justification to use «regular» (standard) deep geoelectrical section, which can serve as a reference when estimating electroconductivity parameters of anomalous blocks of the Earth crust.

Ratio between values of apparent resistivity, measured at maximums of equatorial and axial curves of frequency sounding (within the limits of a quasi-stationary wavezone) does not exceed 20 % almost in all observation points. It allows to come to the conclusion that at the depths from 10-15 to 50-70 km Earth crust (lithosphere) is isotropic. Anisotropy coefficient does not exceed 1.2.

Against relatively homogenous geoelectrical section of the Baltic shield lithosphere in the north-western part of Karelia megablock and Central Finland, a zone of decreased apparent resistivity (Fig.8, *b*) is clearly outlined. This zone encloses area of about 80 thousand km^2. An integral parameter of lithosphere conductivity is transverse resistivity *T*.

DOI: 10.18454/PMI.2017.2.178

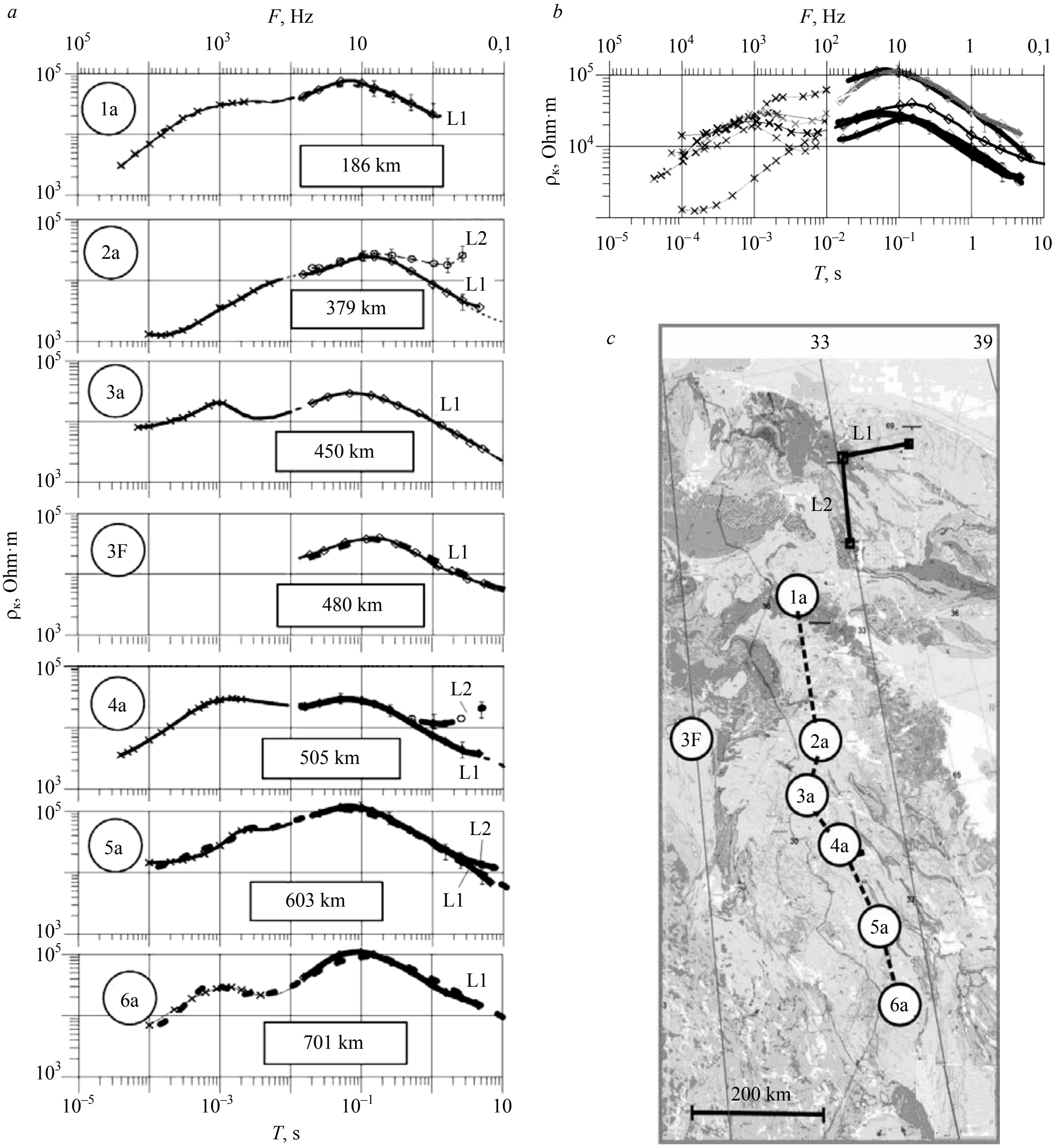

Fig.6. Results of frequency sounding with parallel (equatorial) positioning in the field of latitudinal line L1:
a – curves of apparent resistivity in points 1a-6a and 3F; *b* – cumulative diagram of apparent resistivity curves;
c – position of line L1 and profile 1a-6a

Value of T after the inversion is defined as follows:

$$T = \sum_{i=1}^{i=n} h_i \cdot \rho_i \ ,$$

where h_i – thickness and ρ_i – resistivity of i^{th} layer of the lithosphere.

Background, «regular» value of transverse resistivity equals about $5 \cdot 10^9$ Ohm·m^2. Within the detected anomaly its value is reduced to 10^9 Ohm·m^2 and lower. Contours of the anomaly are shown with T isolines (bold solid lines – $1 \cdot 10^9$ and $2 \cdot 10^9$ Ohm·m^2) and diagonal hatching in Fig.8, *a*. The anomaly is also confirmed by three points 1F-3F, measured on the territory of Finland.

DOI: 10.18454/PMI.2017.2.178

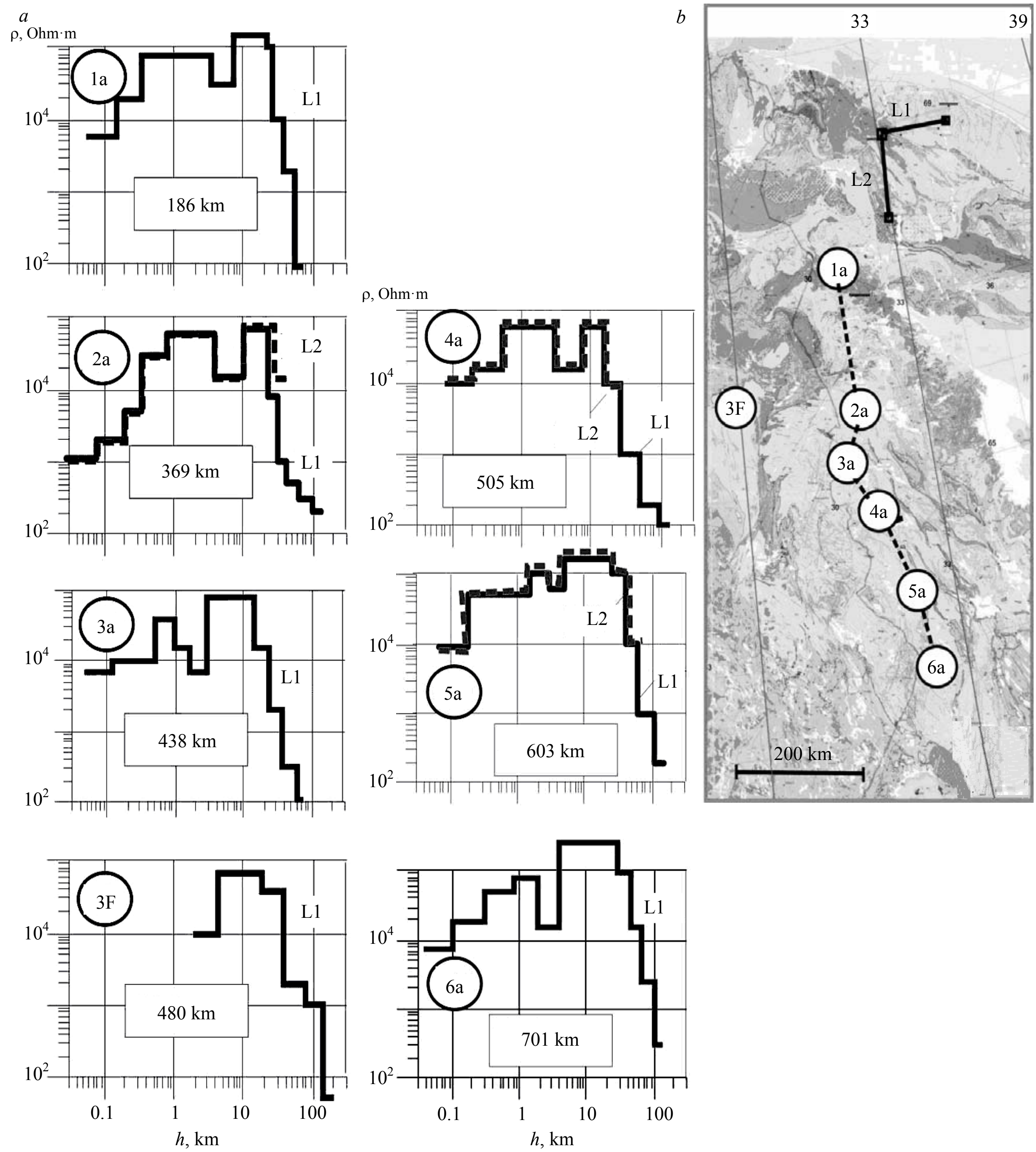

Fig.7. Results of solving inverse problem of deep frequency sounding in the field of lines L1 and L2 in the FENICS experiment for profile 1a-6a and point 3F (*a*) and position of sounding points and power lines (*b*)

In Fig.8, *b* contours of transverse resistivity anomaly are combined with a generalized geological map of the region [4]. However, no matches between the location of *T*-anomaly and the map of surface geology have been found. Comparison of anomaly contours to the map of crustal electrical conductivity [18], presented in Fig.8, *d* did not reveal any common features, either. Such «mismatch» points to a deeper character of the transverse resistivity anomaly, because the nature of crustal conductivity anomalies is totally defined by the presence of electroconducting rocks in the upper part of the crust, approximately 10 km thick.

 DOI: 10.18454/PMI.2017.2.178

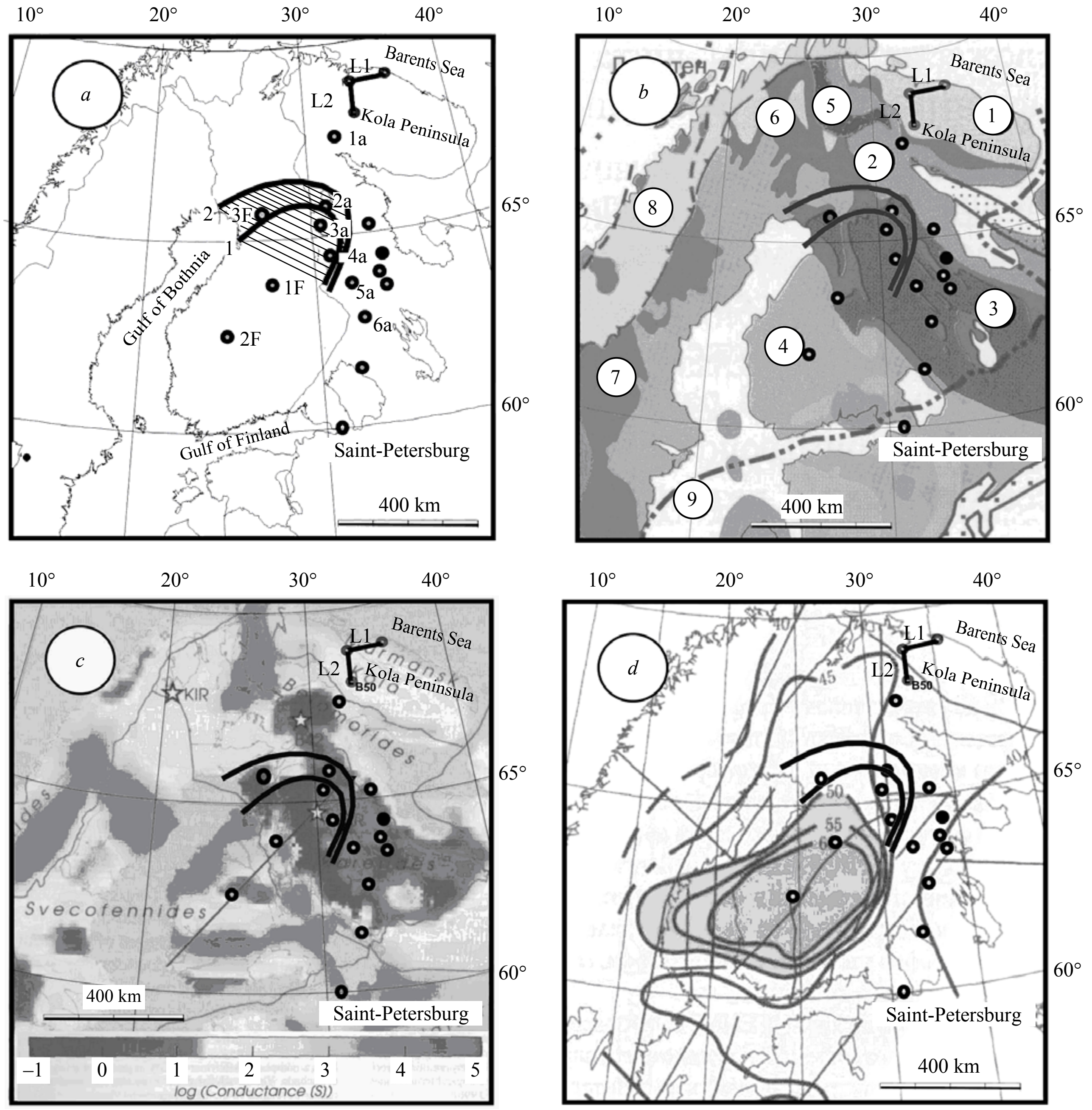

Fig.8. Results of FENICS experiment in isolines of transverse resistivity
(bold solid lines 1 – $1\cdot10^9$ and 2 – $2\cdot10^9$ Ohm·m^2) T (*a*) and their comparison to geology [4] (*b*), crustal conductivity anomalies [15] (*c*) and isodepth scheme of Moho boundary [10] (*d*).

Bold circles – observation points in the course of FENICS-2014 experiment. Points 1a-6a in Fig.8, *a* – section of the profile, presented in Fig.6, 7; points 1F-3F – position of station FMTU-2008 (M.Smirnov, University of Oulu, Finland) in the region of transverse resistivity anomaly. Numbers in circles in Fig. 8, *b* stand for: 1-3 – Archean complexes (1 – Kola, 2 – Belomorsk, 3 – Karelia); 4 – Svekofensky Proterozoic complex; 5 – granulite belt; 6 – greenstone belt; 7 – metavolcanites; 8 – caledonites; 9 – boundary of the Russian platform

In Fig.8, *d* position of T isoline is in good agreement with location of the Moho anomaly, detected in Central Finland using seismic data [10] and later described in paper [13]. In the north-east, T isolines contour a large area where Moho boundary reaches the depth of 60 km. It should be noted that, according to seismic data, for the major part of Fennoscandian schield the thickness of the crust does not exceed 40 km.

A decrease of lithospheric resistivity in the anomalous zone, attributed to the depth of 50-60 km, is apparently caused by trace element conductivity, associated with defects in the crystalline

DOI: 10.18454/PMI.2017.2.178

structure, because free fluids should be absent at such depths, due to overall high resistivity of the matter (over 100 thousand Ohm-meters) and «forcing out» of fluids to the surface under the influence of lithostatic pressure [11].

Conclusions

1. A unique experiment has been carried out, dedicated to deep frequency sounding of Fennoscandian shield lithosphere, using two mutually orthogonal industrial power lines in the frequency range of 0.1-200 Hz and distances up to 856 km between transmitting lines and receiving stations.

2. High level of horizontal homogeneity (one-dimensionality) has been observed in the geological section of the lithosphere in the eastern part of Baltic shield for depths ranging from 10-15 to 50-70 km and anisotropy coefficient not higher than 1.2.

3. A zone of decreased transverse resistivity (10^9 Ohm·m^2) has been detected, which corresponds to the area where Moho boundary reaches the depth of 55-60 km, detected by seismic methods in the western part of Karelia and central Finland.

Acknowledgements. *This work has been carried out with the support of research grant 13-05-12044 by Russian Foundation for Basic Research. Authors also express their gratitude to their colleague from University of Oulu M.Yu.Smirnov for his participation in observations and for the results he provided.*

REFERENCES

1. Van'yan L.L. Electromagnetic Sounding. Moscow: Nauchnyi mir, 1997, p. 218 (in Russian).

2. Barannik M.B., Danilin A.N., Efimov B.V., Kolobov V.V., Prokopchuk P.I., Selivanov V.N., Kopytenko Yu.A., Zhamaletdinov A.A. High-Voltage Rectifier of the «Energy-2» Generator for Electromagnetic Sounding and Monitoring of Earthquake Source Zones. *Seismicheskie pribory*. 2009. Vol. 45. N 3, p. 5-13 (in Russian).

3. Barannik M.B., Danilin A.N., Efimov B.V., Kolobov V.V., Prokopchuk P.I., Selivanov V.N., Shevtsov A.N., Kopytenko Yu.A., Zhamaletdinov A.A. High-Voltage Power Inverter of the Generator «Energy-2» for Electromagnetic Soundings and Monitoring of the Earthquake Source Zones. *Seismicheskie pribory*. 2009. Vol. 45. N 2, p. 5-23 (in Russian).

4. Glaznev V.N. Integrated Geophysical Model of the Lithosphere of Fennoscandia. Apatity: KaeM, 2003, p. 252 (in Russian).

5. Zhamaletdinov A.A., Shevtsov A.N., Korotkova T.G., Kopytenko Yu.A., Ismagilov V.S., Petrishchev M.S., Efimov B.V., Barannik M.B., Kolobov V.V., Prokopchuk P.I., Smirnov M.Yu., Vagin S.A., Pertel' M.I., Tereshchenko E.D., Vasil'ev A.N., Grigor'ev V.F., Gokhberg M.B., Trofimchik V.I., Yampol'skii Yu.M., Koloskov A.V., Fedorov A.V., Kor'ya T. Deep Electromagnetic Sounding of the Lithosphere in the Eastern Baltic (Fennoscandian) Shield with High-Power Controlled Sources and Industrial Power Transmission Lines (FENICS Experiment). *Fizika Zemli*. 2011. N 1, p. 4-26 (in Russian).

6. Zhamaletdinov A.A. Conductivity Model of the Lithosphere as a Result of Research with Controlled Field Sources (Baltic Shield, Russian Platform). Leningrad: Nauka, 1990, p. 159 (in Russian).

7. Kolobov V.V., Barannik M.B., Zhamaletdinov A.A. Generating-Measuring Complex «Energy» for Electromagnetic Sounding of the Lithosphere and Monitoring Seismically Active Areas. St. Petersburg: SOLO, 2013, p. 240 (in Russian).

8. Kraev A.P., Semenov A.S., Tarkhov A.G. Ultradeep Electrosounding. *Razvedka nedr*. 1947. N 3, p. 40-41 (in Russian).

9. Velikhov E.P., Zhamaletdinov A.A., Sobchakov L.A. et al. Experience of Frequency Electromagnetic Sounding of the Earth Crust using Powerful ULF-range Antennas. *Doklady Akademii nauk*. 1994. Vol. 338. N 1, p. 106-109 (in Russian).

10. Pavlenkova N.I., Morozov A.F., Mezhelovskii N.V. The Structure of the Lithosphere of the Baltic Shield according to the NHS. Structure and Dynamics of the Lithosphere of Eastern Europe. Moscow: Geokart, GEOS, 2006. Iss. 2, p. 33-58 (in Russian).

11. Rodkin M.F. The Role of the Deep Fluid Regime in Geodynamics and Seismotectonics. Moscow: Nats. Geof. Kom., 1993, p. 194 (in Russian).

12. Zhamaletdinov A.A., Shevtsov A.N., Tokarev A.D., Kor'ya T. Frequency Electromagnetic Sounding of the Earth's Crust in the Central Finland Granitoid Complex. *Izvestiya RAN. Fizika Zemli*. 2002. N 11, p. 54-68 (in Russian).

13. Sharov N.V., Mitrofanov F.P. Velocity Heterogeneities of the Lithosphere Fennoscandian (Baltic) Shield. *Doklady Akademii nauk*. 2014. Vol. 454. N 2, p. 221-224 (in Russian).

14. Shevtsov A.N. Direct and Inverse Problems of Frequency Electromagnetic Sounding with Industrial Power Lines. Theory and Methods of Deep Electromagnetic Soundings on Crystalline Shields. Apatity: Izd-vo KNTs RAN, 2006, p. 171-181 (in Russian).

15. Korja T., Engels M., Zhamaletdinov A.A., Kovtun A.A., Palshin N.A., Smirnov M.Yu., Tokarev A.D., Asming V.E., Vanyan L.L., Vardaniants I.L. and the BEAR Working Group. Crustal Conductivity in Fennoscandia – a Compilation of a Database on Crustal Conductance in the Fennoscandian Shield. *Earth, Planets and Space*. 2002. Vol. 54, p. 535-558.

16. Velikhov Ye.P., Zhamaletdinov A.A., Belkov I.V., Gorbunov G.I., Hjelt S.E., Lisin A.S., Vanyan L.L., Zhdanov M.S., Demidova T.A., Korja T., Kirillov S.K., Kuksa Y.I., Poltanov A.Y., Tokarev A.D., Yevstigneyev V.V. Electromagnetic Studies on

DOI: 10.18454/PMI.2017.2.178

the Kola Peninsula and in Northern Finland by Means of a Powerfull Controlled Source. *Journal of Geodynamics*. 1986. Vol. 5. Iss. 2, p. 237-256.

17. Khintchine Alexander. Korrelationstheorie der stationären stochastischen Prozesse. *Mathematische Annalen*. 1934. 09 (1), p. 604-615.

18. Korepanov V.Ye. Electromagnetic Sensors for Microsatellites. Proceedings of IEEE «Sensors», 2002, p. 1718-1722.

19. Smith J.O. Spectral Audio Signal Processing. Stanford, California: W3K Publishing, 2011, p. 674.

***Authors*: Aleksandr N. Shevtsov,** *Candidate of Physics and Mathematics*, *Senior Researcher*, *anshev2009-01@rambler.ru* (*Geological Institute of the Kola Science Centre of the RAS*, *Apatity*, *Russia*), **Abdulkhai A. Zhamaletdinov,** *Doctor of Geological and Mineral Sciences*, *Chief Researcher*, *abd.zham@mail.ru* (*Geological Institute of the Kola Science Centre of the RAS*, *Apatity*, *Russia*), **Vitalii V. Kolobov**, *Candidate of Engineering Sciences*, *Leading Researcher*, *1_i@mail.ru* (*Centre for Physical and Technological Problems of Energy in Northern Areas of the Kola Science Centre of the RAS*, *Apatity*, *Russia*), **Maksim B. Barannik,** *Researcher*, *maxbar@ien.kolasc.net.ru* (*Centre for Physical and Technological Problems of Energy in Northern Areas of the Kola Science Centre of the RAS*, *Apatity*, *Russia*).

The paper was accepted for publication on 7 July, 2016.