Глава 4. Методика и техника возбуждения и регистрации СНЧ электромагнитного поля.

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Abstract - An overview of current deep studies with the use of a new type of electromagnetic source in the extremely low frequency (ELF) range is presented. The results of the experimental explorations with the “Zevs” ELF installation located in the north of the Kola Peninsula are reported. The soundings in the near-field zone, DC soundings, soundings in the frequency and transient-field regimes in ore regions, and deep soundings in the wave zone, at a distance of up to 1100 km, are described. The influence of the ionosphere and displacement currents on the results of deep soundings was analyzed. The possible use of the “Zevs” ELF radio installation in applied and basic geophysics is discussed.

Introduction

This paper is devoted to the analysis of possibilities to use a new type of controlled source - a powerful radio transmitting installation of extremely low frequency (ELF) range-in deep electromagnetic studies. Before describing the installation and the initial results, it is appropriate to review previous studies in this direction.

The history of electromagnetic soundings of the Earth using powerful controlled sources began in the mid-1940s, when the first deep soundings were carried out in the Gulf of Finland [Kraev et al.*,* 1947]. The soundings used a grounded electric line submerged in the sea and fed by a direct (pulse) current. The power installation composed of a battery of lead-acid cells provided a current of up to a thousand amperes in the line. The observations were conducted along the ground and sea lines and used an analog-type measuring apparatus. These works, with a separation of up to 75 km, showed that a conductive layer exists in the crust, at depths of 10 to 20 km. Around the same time, geoelectric measurements were performed in Sweden, with the use of grounded electric lines of up to 200 km in length, with the purpose of studying the influence of ground currents on underground service lines [Lundholm, 1946]. From these works, it was proposed that the electrical conductivity of the crust, at a depth of about 30 km, increases.

The results of soundings in the Gulf of Finland lent impetus to the further development of deep soundings in the USSR, which were based mainly on the magnetotelluric method developed by A.N. Tikhonov [1950] and L. Cagniard [1953]. Along with this, the technique of soundings with controlled sources continued to improve. Of the most important results, we note a series of deep dc soundings carried out in the United States and Canada in 1963-1968, with the use of mobile sources and sections of power lines [Cantwell et al.*,* 1965; Samson, 1969]. The studies were made in connection with the choice of the territory for installation of antennas for the underground and land-based low-frequency wireless communication that could be used to detect electromagnetic signals from distant nuclear explosions, to perform the communication with submerged objects, and to solve other tasks. The working separations reached 200 km for the line length from 37 to 218 km.

The studies in the Dallas area [Cantwell et al.*,* 1965] indicated a strong inhomogeneity of the underlying basement. The average resistivity of the basement in the eastern sector of the examinations reached 20000 Ω·m, whereas in the southern sector, at a distance of about 200 km, the resistivity was only 10 Ω·m. According to the quoted authors, the cause of such great variations in the crustal resistivity at depth is related to the possible effect of a E-W-oriented deep-seated fault. From data of various authors, the depth to the conductive layer in the crust ranges from 70 km in North America [Cantwell et al.*,* 1965] to 10 km in Canada [Samson, 1969].

These and other results suggested an abrupt electrical inhomogeneity in the Earth's deep structure. This, in turn, led to the abandonment of possible distant underground wireless communication with the use of low-frequency electromagnetic waves, which propagate over hundreds and even thousands of kilometers in the poorly conductive middle crust. In this case, the latter might serve as an unusual waveguide between two highly conductive shells: the fluid-containing upper crust with a thickness of 5-10 km and the high-temperature conductive lower crust at depths of 40-50 km.

During 1965-1976, a wide program of deep soundings was performed in southern Africa [Van Zijl, 1969; Van Zijl and Jubert, 1975; Blohm et al.*,* 1977]. The DC soundings were carried out using the dominantly four-electrode Schlumberger array. The Cabora-Bassa high voltage 1250-km-long DC line and telephone lines were used during the period that it was made operational. The maximum AB/2 separations reached 620 km. The results of these many-year studies were generalized by Van Zijl and Jubert [1975]. Unlike the results for North America, they concluded that the crustal conductive layer exists throughout the southern African crystalline shield, at depths of 10-20 km. The nature of the conductive layer was related to the dehydration of the rocks.

A number of deep soundings were also carried out in Central Europe (in France), with the use of DC sources [Migaux et al., 1960] and the earth current of electrified railroads [Mennier, 1969]. The high electrical conductivity of the sedimentary cover and the restricted separations (a few tens of kilometers) in these experiments did not allow the study of the lower crust structure.

In the early 1970s, the technique of soundings with controlled sources was supplemented by a pulse magnetohydrodynamic (MHD) generator with a power of up to 80 MW. A series of experiments was carried out in the Urals, Pamir, and the Kola Peninsula [Astrakhantsev et al., 1977; Velikhov and Volkov, 1982; Velikhov et al., 1984; Zhamaletdinov, 1982]. The results of the Ural MHD experiment conducted on a restricted network of profiles were found to be affected by a thick conductive fault. Consequently, in spite of the great depth of these studies, up to 40 km, only ambiguous results for the electrical model of the crust in this region were obtained. The experiment with the Khibiny MHD source on the Kola Peninsula used areal measurements and a network of regional profiles covering northern Karelia and adjacent parts of Finland and Norway, along with the Kola Peninsula. The observations were used to develop a block model for electrical conductivity in the upper crust and to identify homogeneous poorly conductive basement blocks, on which the measuring sites were then concentrated. These studies were intended for the deep sounding of the lithosphere through its total thickness. The current in the antenna (flooded circuit) reached 22000 A. The measurements were made at distances of up to 600-700 km from the source.

These studies allowed the assessment of the character of variations in the crustal electrical conductivity to depths of 100-150 km in a frequency range of 0.05- 2 Hz and gave an overall estimate of the transverse resistivity of the crust $T = h \cdot \rho$ (R is the thickness and ρ is the resistivity of poorly conductive crust) reaching $2 \cdot 10^{10}$ Ω·m^2 [Zhamaletdinov, 1982, 1990]. Such a high transverse resistivity was confirmed in the order of magnitude by the model calculations [Vanyan et al., 1989] and suggested the absence of conductive layers in the crust, at least, to a depth of 30-40 km. However, this conclusion is at variance with the majority of the previous results derived from deep soundings with powerful controlled sources and magnetotelluric (MT) and audiomagnetotelluric (AMT) soundings [Jones, 1982; Kovtun et al., 1986].

During approximately the same years, deep sounding experiments began in the Soviet Union with the use of industrial power lines. Glaze-melting installations [Sapuzhak and Enenstein, 1980] and DC power lines [Zhamaletdinov et al., 1981, 1990] were employed as current sources. In the experiments with the Volgograd-Donbass 800 kV DC power line, 473 km long, the current reached 1400 A in the doubling regime. However, in spite of the large achieved separations (up to 504 km), the curve of apparent resistivity from the distant sounding did not exceed the bounds of the ascending asymptote, which suggested the absence of conductive layers in the crust, at least, up to a depth of 2030 km and the presence of a high transverse resistivity of the crust (on the order of 10^{10} Ω·m^2), which impedes the penetration of current to large depths.

Thus, the analysis of the deep soundings presented above shows that the basic problem on the electrical conductivity model for the crust has not yet been resolved, since the results obtained by various researchers with the use of different methods are at great variance. Further searches for unambiguous solutions must lie in the manner that alternative methods of deep electromagnetic soundings are applied.

A new step in the technique of Earth soundings is related to the application of ELF radio transmitting antennas. The first experiments in this direction were carried out in 1990-1993 [Velikhov et al., 1994]. Studies on the development and creation of the ELF antennas and on the propagation and detection of low-frequency electromagnetic oscillations in the Earth-ionosphere waveguide began in the Soviet Union and the United States in the mid-1960s. The purpose of these works was to solve the problems of wireless communication with submerged objects and of the detection of underground nuclear explosions [Ames et al., 1963; Keller et al., 1966; Bernstain et al., 1974]. The attractiveness of using extremely long radio waves for these purposes is related to the following unique features of the ELF range.

(1) The ELF waves propagating in the Earth-ionosphere waveguide penetrate sufficiently deeply into the waveguide walls. For a frequency of 100 Hz and lower, the maximum depth reaches 100 m in the ocean and 10-15 km in crystalline shields.

(2) The properties of the waveguide are such that the attenuation of ELF waves, inferred from experimental data, decreases as the frequency decreases, from 1020 dB/1000 km for a frequency of 1 kHz to 12 dB/1000 km for a frequency of 100 Hz. This provides virtually global communication with remote objects for a fixed transmitter position.

(3) Due to their great length, the parameters of ELF wave propagation minimally depend on the ionosphere disturbances. This provides a higher stability of communication compared to high-frequency transmitters.

1. Methods of ELF wave radiation

An important feature placing specific constraints on the design of ELF antennas is their small linear dimensions compared to the wavelength in air, which leads to problems regarding their high reactive impedance. In the vertical antenna, while generating the ELF waves, electrical break-down occurs before the necessary current is reached. Consequently, an optimum vibrator for the ELF radiation is a horizontal line grounded on its both ends. The principal requirements to such an antenna are a sufficiently large electric moment $P = J \cdot l$ (where J is the current in the antenna and l is the antenna length) and a sufficiently low conductivity in the underlying half-space. The latter requirement is caused by the necessity to obtain the maximal radiating magnetic moment. The grounding of the antenna ends provides a path for the returning earth current. The current is concentrated at a depth approximately equal to $\delta/\sqrt{2}$, where $\delta \approx \sqrt{2\rho/\omega\mu_0}$ is the skin thickness in the Earth. At distances exceeding 3δ, the field of the horizontal grounded cable can be represented by a vertical magnetic loop with an area of $L\delta/\sqrt{2}$.

The generator power required to produce the necessary magnetic moment of the antenna is determined by the total complex resistivity at the antenna input. The active component is created by the resistance of the grounding systems, the lead, and the returning path of the earth current. The earth current resistance R_e is produced by the Foucault currents in the Earth. The value of R_e is usually estimated assuming that the earth current flows in a half-cylindrical hollow provided that $l > \delta$; in this case, $R_e = \omega\mu_0/8$ [Bernstain et al.*,* 1974].

The grounding systems are a special problem in the design of the ELF antennas. The requirement of the minimum conductivity of the ground beneath the antenna leads to the necessity of using the ground connections occupying large areas in order to diminish their resistivity. The grounding resistivity R is estimated to an accuracy sufficient for practice by the formula $R = \rho/l$ for a linear grounding with length l and by the formula $R = \rho/P$ for a plane grounding, where P is the grounding perimeter (in m). Hence, one can see that, for the average resistivity of the ground $\rho = 10^4 \Omega \cdot m$, the transient grounding resistance on the order of 2-3Ω is provided by a grounding with an area of no less than 1 km^2.

The reactive impedance is the sum of the inductive and capacitive components. For the end-grounded feeder, the effect of a distributed capacitance is similar to that of a resistor placed in parallel with the grounding resistor. In this case, the wire will be under the same potential, and for a low grounding resistance, the influence of the capacitive reactance can be neglected. Consequently, the wire inductance makes the main contribution to the reactive impedance of the ELF antenna. Inductive reactance R_L reflects the accumulation of energy in the magnetic field and is proportional to the field frequency

$$R_L = \omega L, \Omega,$$

where L is the running inductance of the wire lying on the ground. In practical calculations, L is set as $3 \cdot 10^{-3}$ H/km [Veshev, 1980]. For a frequency of 100 Hz, the inductive reactance of the 100-km-long antenna is approximately 180Ω. In order to achieve a purely resistive load on the circuit, the matching capacities are introduced in a series connection to the line so as to form a series resonance *RLC* circuit. The further matching of the circuit is made by adjusting the circuit quality factor.

2. Experiments with the ELF transmitters

At the present time, two projects that practically realized the ELF communication are known: "Sangwin" (United States) and "Zevs" (Russia). In the course of the realization of the "Sangwin" project, a few transmitting antennas were first constructed [Bernstain et al.*,* 1974; Bannister, 1974]. One of them was installed in North Carolina in 1966-1967. A 176-km-long horizontal wire served as the transmitting antenna and was fed by a current on frequencies of 78 Hz, 156 Hz, etc. The observations were performed along a 4900-km trace (up to Iceland).

Another series of observations was conducted in the state of Wisconsin in 1971-1973 (United States). The transmitting VIU antenna was composed of two orthogonal grounded lines, each of which had an individual power supply at the central point, in a frequency range of 45 to 75 Hz. Each of the antennas was 22.5 km long, and the maximum current was 300 A. The directivity diagram of the antenna could be controlled by choosing the phase difference between the currents in two vibrators, which provided the omnidirectional pattern. The location of the VIU antenna and the sites of signal detection are shown in Fig. 1. The measurements were carried out at shore stations and onboard an atomic submarine that passed across the Pacific Ocean. The signals were received at depths of up to 100 m and at distances of up to 11 000 km.

The positive results obtained served as a basis for designing the main "Sangwin" transmitting antenna, in which the length of the transmitting grounded line was made longer due to the use of a "lattice" of vibrators. The use of several parallel lines allows the construction of a more compact antenna, the moment of which is equal to the geometrical sum of the moments of all the lattice elements.

In the Soviet Union, studies in the field of ELF wireless communication were performed at several research sites, and one of them is located in the north of the Kola Peninsula. In the first stages of the ELF developments in this region, the Kola-Serebryanka industrial 110-km power line was used in the period of its initialization. This line provided the first series of successful experiments on the detection of ELF signals at distances of up to 4000-5000 km.

The next step was the creation of a specially radiating system called "Zevs". It consists of two parallel asymmetric grounded 60-km-long vibrators fed from two sinusoidal-voltage switch-generators that were installed at each of the groundings. The transmitter provides the antenna current of up to 200-300 A, in a frequency range of 20 to 200 Hz [Velikhov et al.*,* 1994]. The sinusoidal current in the antenna can be given on the frequency network with a step of 0.1 Hz. The frequency of the master oscillator is determined by the "Giatsint" system with an accuracy of variations no worse than 10^{-7} s.

The "Zevs" antenna is located on the Murmansk crystalline block of the Archean age. The crust in this region is characterized by very high resistivity exceeding $10^5 \Omega \cdot m$ at depths of about 10-15 km [Zhamaletdinov et al.*,* 1991]. At the time of designing the "Zevs" antenna, extensive geoelectrical observations were performed in this region with the purpose of choosing suitable traces for air power lines and the sites of their grounding. The studies were headed by the staff members of the Saint Petersburg University, Prof. A.V. Veshchev and Assistant Prof. A.V. Yakovlev. The electrical exploration revealed the local zone of low resistivity suitable for the siting of power groundings and helped to design the radiation parameters of the antenna.

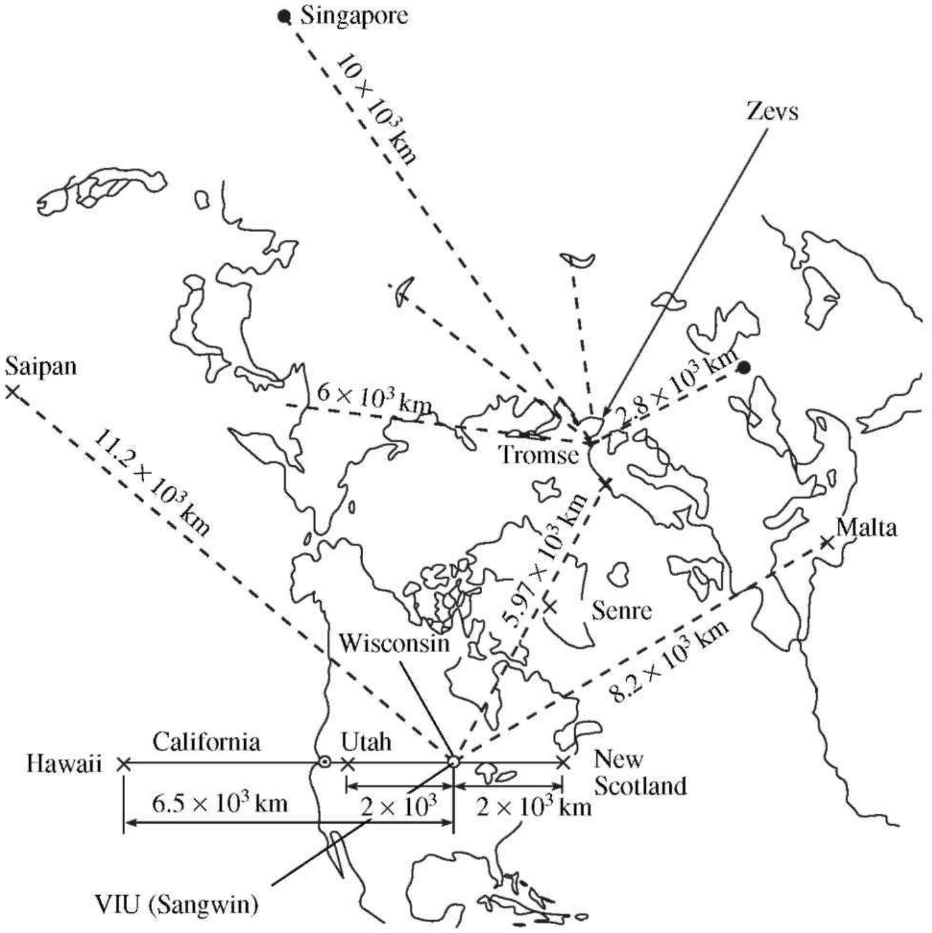

Fig. 1. Arrangement of the Sangwin and “Zevs” ELF antennas and the location of detection sites.

The successful location of the “Zevs” antenna and high technical parameters of the power installation provided the radiation power sufficient for the reliable detection of signals at a distance of up to 10000 km in the Atlantic and Pacific Oceans (Fig. 1). The estimated equivalent magnetic moment of the antenna is on the order of $2{\cdot}10^{11}$ A·m^2.

Many methods for calculating the parameters of propagating ELF waves have been developed [Al'pert, 1988; Galleis, 1968; Bernstain et al., 1974; Akindinov et al., 1978; Makarov et al., 1993]. The ELF field is believed to propagate in the Earth-ionosphere waveguide as a vertically polarized, transversely electric TE mode. It includes the horizontal component H_φ (longitudinal relative to the waveguide boundaries) and the vertical (transverse) electrical component Ez. Due to the Leontovich boundary conditions, component H_φ produces electric field E_θ at the Earth's surface. In this case, a part of the energy is scattered downwards as a plane electromagnetic wave provided that $k_0 << k_e$, where k_0 and k_e are the wave numbers of air and the lower half-space (the Earth), respectively. Intensity E_θ of the horizontal field is determined by the input impedance of lower half-space Z_e

$$E_\theta = Z_e H_\varphi, \text{ where } Z_e = \sqrt{\rho_e \omega \mu_0}\ .$$

The deep sounding of the Earth in the ELF antenna field can be performed by studying impedance E_θ / H_φ.

The table lists the calculated electric and magnetic components of the ELF antenna field for the parameters of the “Zevs” source, at the points located along the antenna axis, at different distances from the source. The calculations were made by the formulas given by Bern-stain et al. [1974] and Akindinov et al. [1976]. The adopted methods of calculations differ mainly in the procedures of allowing for the attenuation coefficients of ELF waves in the Earth-ionosphere spherical waveguide. Both quoted papers used the same frequency dependence of the attenuation coefficients, which is based on the experimental study of the lightning discharge propagation parameters, the Schuman resonances, and artificial signals from the “Sangwin” source on frequencies of 45 and 75 Hz. The calculations took into account the energy of an incident wave and the wave passing around the Earth along the great circle. The electric field intensity was derived from magnetic field H_φ through the impedance of a homogeneous half-space with a resistivity of $10^4\Omega\cdot$m. The remaining parameters are indicated in the note to the table. One can see that the field values obtained by the formulas of Akindov et al. [1976] are 30% greater than those from the formulas by Bernstain et al. [1974].

Comparative table of the ELF “Zevs” field amplitudes calculated by formulas from various sources

r (km)	Bernstain et al., 1974		Akindinov et al., 1976	
	H_φ, 0.1 nT	E_θ, mV/km	H_φ, 0.1 nT	E_θ, mV/km
1000	2.57	0.57	3.67	0.82
2000	1.62	0.36	2.33	0.52
3000	1.20	0.27	1.71	0.38
4000	0.94	0.21	1.34	0.30
5000	0.77	0.17	1.09	0.24
6000	0.66	0.45	0.91	0.20
7000	0.57	0.13	0.77	0.17
8000	0.50	0.11	0.67	0.15

Note: The values accepted in the calculations: the underlying space resistivity is 10 000 Ω·m, the height of the ionosphere is 100 km, the antenna length is 60 km, the current in the antenna is 300 A, the attenuation coefficient is 1dB /1000 km, the azimuth of the receiving point relative to the axis parallel to the dipole arm is 0° (axial installation), the source current frequency is 100 Hz, and the ratio of the light velocity to the phase velocity of the ELF wave is 1.4.

In order to gain an impression of the distribution of the “Zevs” ELF antenna field in the CIS territory, Fig. 2 shows an approximate diagram of isolines of the total horizontal magnetic field at a frequency of 100 Hz, for a current of 300 A in the antenna. For longer distances (above 3000 km), when the Earth's sphericity must be taken into account, the calculations were based on the formulas from the paper [Bernstain et al., 1974]. For distances shorter than 3000 km, the electromagnetic field of the “Zevs” source was calculated by the formulas for a horizontal electric dipole in a plane layered medium [Shevtsov, 1995], which are present in section 5 below. The main seismic risk zones in the CIS territory, which are interesting for electromagnetic monitoring with the purpose of earthquake prediction, are hatched in Fig. 2. In the diagram of isolines, one can see that the magnetic field varies from about 0.05-0.07 pT in the seismic risk zones of the northern Caucasus to about 0.04 pT in the Kamchatka region of operating volcanos. As shown below, the modern apparatus is capable of detecting these signals. Records of ELF signals were obtained at many sites in the CIS territory (in Vladivostok, Transbaikalia, the Crimea, and the Caucasus), and the observed field amplitudes were found to be close to those calculated in Fig. 2.

The “Zevs” installation is presently a unique operating object of ELF radio communication. Nevertheless, its obvious advantages described above have a number of constraints. First of all, it is a one-way type of connection, since large wavelengths require enormous antennas with linear sizes of tens and up to hundreds of kilometers. The high losses on radiation require the application of powerful sources. The conversion coefficient is, on average, 10^{-5}; i.e., each watt of the radiated energy is related to an expenditure of generator energy of up to 100 kW.

Nevertheless, the rapid development of computerized digital data-processing methods, the appearance of modern low-noise antennas for detecting weak signals, as well as wide possibilities for using satellite systems for the synchronization of source and receiver open new ways to develop ELF wireless communication. The principal prospects are related to the development of multipurpose systems intended, on the one hand, to solve the problems of basic and applied geophysics, and on the other hand, to further expand the possibilities of ELF systems for working in the interests of the Russian navy. This paper is devoted to the results of studies obtained with the “Zevs” antenna for solving geological and geophysical problems.

3. Soundings in the near-field zone of the ELF antenna

Already, in designing the “Zevs” radio transmitter in this region, vertical electromagnetic soundings were carried out to choose the trace of an air power line and areas for grounding. These works continued with the use of natural and controlled electromagnetic sources for improving the radiating parameters of the antenna.

In 1989, the problem on the use of the “Zevs” ELF antenna was stated in the framework of the program "Conversion" for solving the tasks of deep sounding of the crust and studying the ore field structure.

In the first step, in 1990-1991, a series of deep DC pulse soundings was performed by connecting an ERS-67 external source of the 29-kW power directly to the ends of one of the antenna. A current of 25 A was delivered to the line, in the form of alternating rectangular pulses with a pulse spacing of 8 s. The digital detection with the subsequent stacking was made with the help of the TsAIS apparatus. Three components of the electric field were measured at each point: two mutually orthogonal and the third component turned at an angle of 45° to the first two components. This allowed the estimation of the direction of the total horizontal vector, along with its modulus. The position of the observation sites was chosen in arbitrary parts of the plane table, depending on the presence of roads (Figs. 3a, 3b). The results were treated and interpreted for the total vector of the horizontal electric field $|\mathrm{E}| = \sqrt{E_x^2 + E_y^2}$ for $\partial E/\partial t \to 0$.

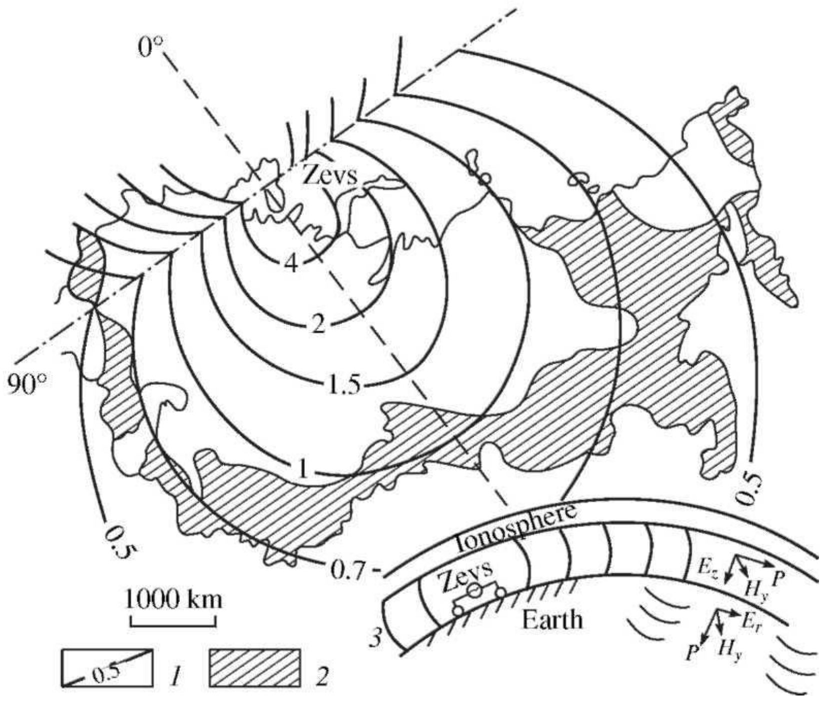

Fig. 2. Isoline pattern of the total horizontal magnetic field from the "Zevs" source in the CIS territory from theoretical calculations. (1) Magnetic field isolines (in 10^{-4} nT), (2) seismic risk zone in the CIS territory, (3) schematic propagation of ELF signals in the Earth-ionosphere waveguide. Dashed-dotted lines are the axial (0°) and equatorial (90°) lines of the "Zevs" source on the map.

The field was normalized with the help of geometrical coefficient *K* defined as a quantity inverse to intensity E_0 of the field created by the superposition of the power line groundings above a homogeneous half-space with ρ= 1Ω·m [Zhamaletdinov et al., 1981].

$$E_0 = \frac{1}{2\pi}\sqrt{r_A^{-4} + r_A^{-4} - \frac{r_A^2 + r_B^2 - L^2}{(r_A r_B)^3}}$$

where r_A and r_B are the distances from an observation point to groundings *A* and *B*, respectively.

The working separation parameter was calculated by the empirical formula $r^{eff} = r_A + 0.5(r_B - r_A)(r_A / r_B)^2$, where $r_A < r_B$.

The calculations of the theoretical curves showed that the adopted parameter of the effective separation allows us to reduce the sounding curves, obtained at various angles to line AB, to a unified comparable form. The soundings with the "Zevs" antenna were combined with the previous soundings by the MHD generator "Khibiny" [Zhamaletdinov, 1990] and with the results of dipole frequency sounding from an additional grounded dipole A_2B_2 (Fig. 3b) on low frequencies corresponding to the near-field zone [Zhamaletdinov et al., 1991]. The obtained results were used to construct a unified curve of distant sounding with a separation of up to 350 km (Figs. 3c, 3d). It can be seen that the apparent resistivity has a large scatter indicating the great inhomogeneity of the upper crust. In most cases, we succeed in establishing the relationship between the abrupt deviations of p_a toward lower values and the location of observation sites in the zones of tectonic disturbances or within specific geological formations characterized by a high content of electron-conducting carbonaceous rocks.

Figures 3c, 3d show two alternative interpretations of the results: the K-type section with a thick poorly conductive crust, including a smooth decrease in conductivity at depths of 30-40km, i.e., at the Moho level (Fig. 3c), and the section with an intermediate conductive layer at a depth of 10-20 km (Fig. 3d). The transverse resistivity of the crust $T = h\rho$ is estimated at $4 \cdot 10^9 \Omega \cdot m^2$, for an average crustal resistivity of 10^5 $\Omega \cdot m^2$ and a crustal thickness of 40 km. One or another of the models is chosen by the interpreter and, until recently, has remained questionable. These rather uncertain estimates exhaust the possibilities of the geometrical (distant) principle in the studies on the deep structure of the crust, since, in the course of increasing the separations and sounding depth, the receiver must move to new geological conditions, which leads to the accumulation of uncontrolled errors.

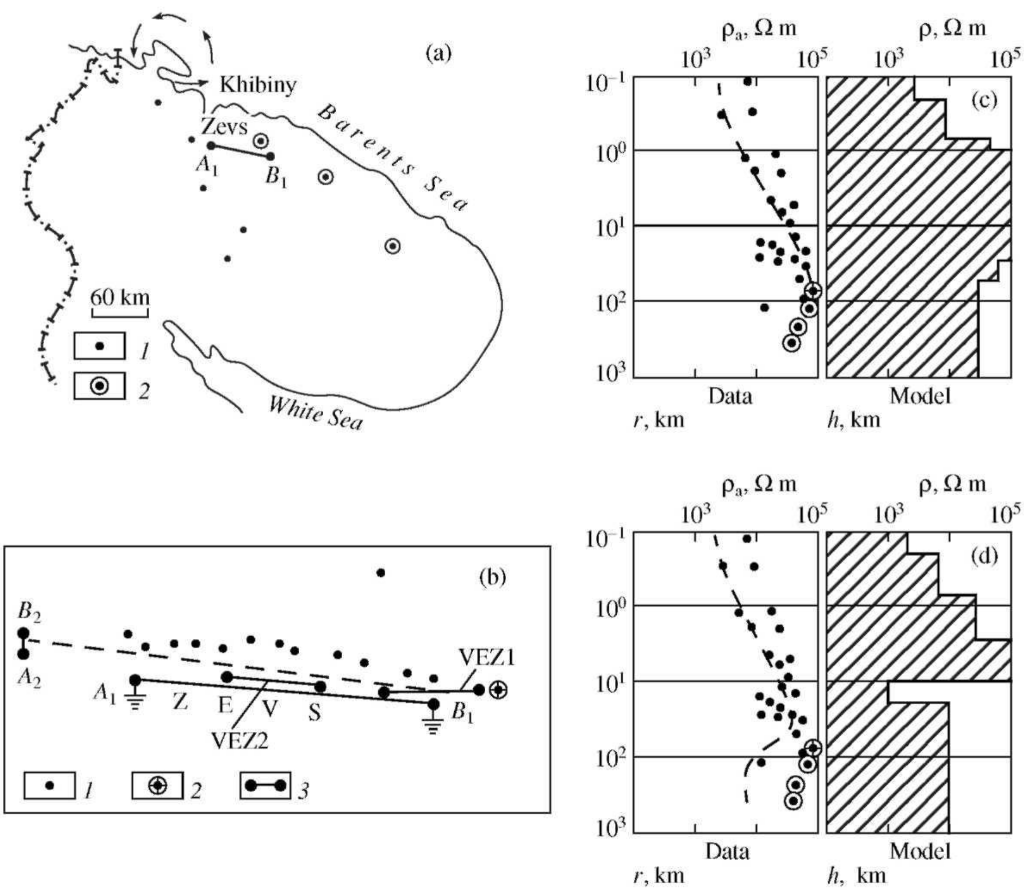

Fig. 3. Results of DC electric soundings in the field of the "Zevs" ELF antenna and Khibiny MHD source in the Kola Peninsula. (a) location of the receiving sites at large distances of 20-400 km from *(1)* the "Zevs" and *(2)* Khibiny sources. (b) location of the sounding sites at small distances from *(1)* "Zevs", *(2)* dipole ERS-67, and *(3)* VEZ (with AB/2 of up to 8 km) sources. (c, d) two fitted versions of the electrical section model.

4. Studies with the "Zevs" source in ore regions

The principal prospects of deep soundings are related to the use of the "Zevs" source in the frequency mode, when the variation in the sounding depth is reached due to the skin effect. As the frequency decreases, the skin thickness increases and so does the depth of the field penetration into the Earth. Such studies were first carried out in the Pana-Tsaga platinum-bearing province, 120 km south of the ELF antenna (Fig. 4). The current was delivered to the line from two sources: the ERS-67 general group in a frequency range of 1 to 1000 Hz and the main "Zevs" power installation in a narrower frequency range of 31.2 to 166 Hz, with a frequency step of $\sqrt{2}$. The measurements were made in 1991 with a single-channel analog receiver working on the super heterodyning principle.

At all the observation sites, we obtained unusual descending curves of apparent resistivity with several bend points. These latter can be formally interpreted as thin conductive layers at depths ranging from 1.7 to 7 km. The soundings were performed at five sites spacing, on average, 10 km apart (Fig. 4b). With such a rare network, it is difficult to closely interpret the data, especially in the geologically complex Pana-Tsaga rivers region. Nevertheless, the regular course of the obtained ρ_ω curves enables us to construct the electrical section (Fig. 4a) in which we observe conductive layers gently sloping toward the north. The uppermost position of the top of the upper conductive layer, at a depth of 1.7 km, was fixed at point 1 (Fig. 4b). This suggests the gently sloping dip of the conductive base toward the northeast. This conclusion agrees with the location of seismic reflection boundaries in Fig. 4a and with the general geological views of a trough-like structure of the region with the same dip of the boundaries toward the north-east.

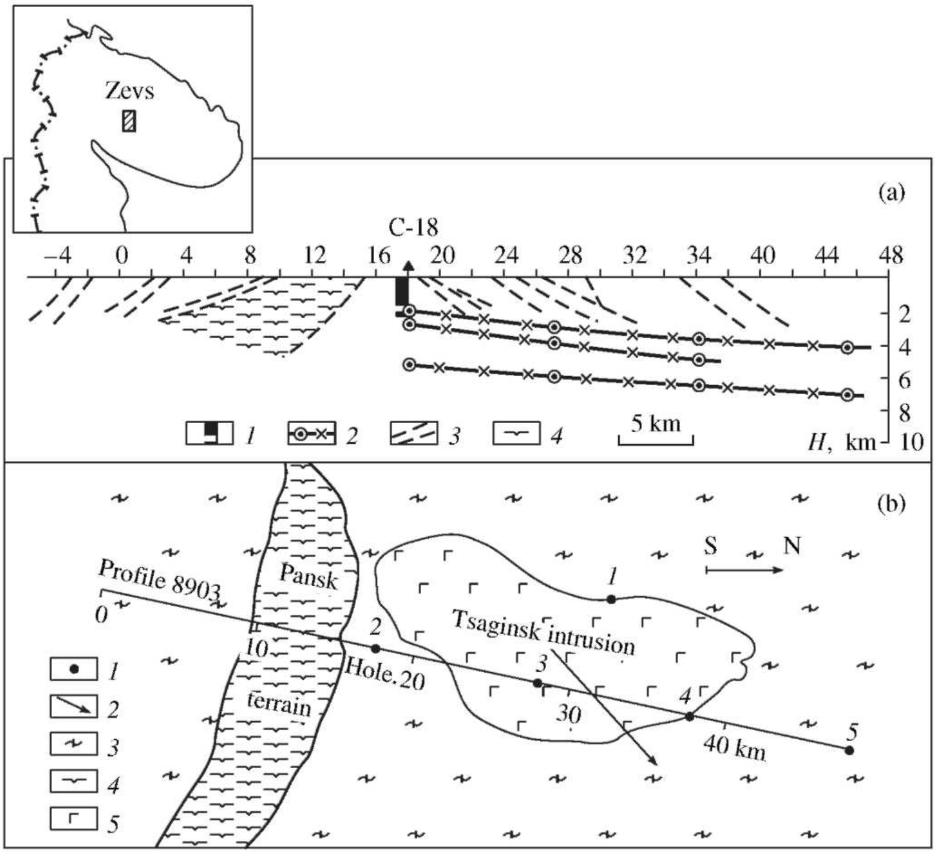

Fig. 4. Results of deep soundings with the “Zevs” source in the areas of the Pana and Tsaga intrusions.
(a) Deep seismogeoelectrical section: *(1)* diagram of the S-18 hole electrical logging, *(2)* conductive layers from the interpretation of soundings with the “Zevs” ELF antenna, *(3)* seismic reflection planes, *(4)* basic and ultra basic rocks in the Pannonian terrain. (b) Location of the observation profile on the geological map in plan: *(1)* points of soundings with the “Zevs” source, *(2)* the direction of dip of the conductive base from sounding results, *(3)* enclosing gneisses, *(4)* Pannonian terrain rocks, *(5)* Tsaga intrusion rocks.

At the northern flank of the Pana layered intrusion hole S-18 was subsequently drilled near the sounding site no. 2. The drilling at a depth interval of 1.7 to 1.95 km revealed the conductive horizon with a resistivity lower than 10^3 Ω·m (Fig. 5c). The logging technique did not give the exact value of resistivity in the conductive layer. Its nature is related to the titanium-magnetite mineralization that controls the position of a promising platinic ore zone. The location of this horizon is satisfactorily consistent to the position of the upper conductive layer found in the deep soundings with the “Zevs” source (Figs. 5a, 5b). The apparent resistivity curves in Fig. 5a were interpreted on the basis of the H-asymptotic of the wave curves shown in Fig. 5a by thin lines drawn at an angle of 63° to the ordinate. A similar result is obtained from interpreting the ρ_ω curve by the Molochnov-Viete method of differential transformations. At the same time, the selected solution to the forward problem gives only a smoothed curve with

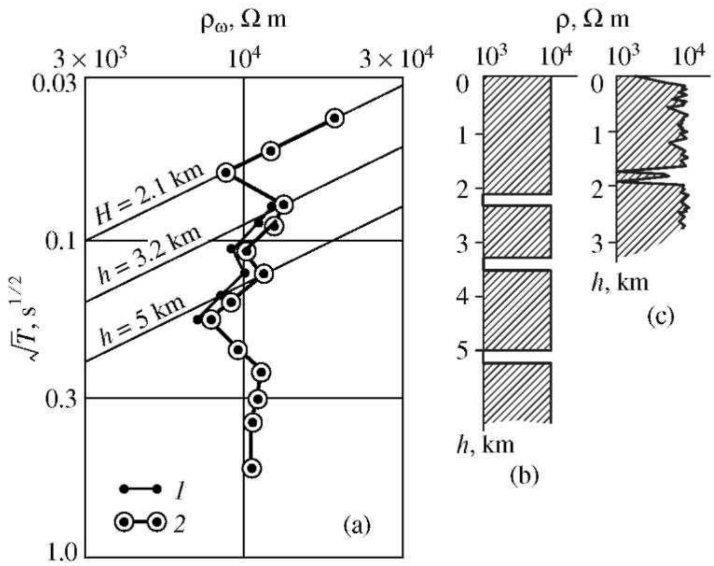

Fig. 5. Example of the fitted electrical section model from soundings with the “Zevs” source in an area of the S-18 hole (Pana-Tsaga region). (a) Apparent resistivity curve, (b) the one-dimensional section fitted by the approximation method, (c) resistivity section from logging data.

a high resolution only for the upper conductive layer and with a low resolution for the two lower layers. Since the intermediate bends in the ρ_ω curve (Fig. 5a) were confirmed by two independent methods of current generation in the "Zevs" antenna, these bends are not noise. Their nature may be caused, to a considerable extent, by regional features of the horizontal inhomogeneity of rocks.

At sites *1* and *2* (Fig. 4), the soundings were also made by using the transient field from the "Zevs" antenna, by generating in it the rectangular signals from the ERS-67 general group, with a period of T = 8 s. The measurements and subsequent processing were conducted in the deep stacking regime. At the same site, the magnetotelluric soundings were subsequently carried out with the use of the TsAIS apparatus [Askerov et al., 1989]. Joint data processing gave the summary curve of the frequency sounding in a frequency range of 0.001 to 1000 Hz. The obtained sounding curves are characterized by a regular drop in the apparent resistivity from about 10^4 Ω·m for the 1000 Hz frequency to about 10^2 Ω·m along the minimal curve for a frequency of 0.001 Hz. This suggests a substantial anomaly in the region, i.e., the possible extension of a unified conductive layer at depth. Such a proposal was first set forward by N.F. Skopenko [1985] on the basis of studies using the small-scale charge method.

Deep soundings with the "Zevs" source were also carried out in the Monchegorsk ore region, with the use of the ERS-67 general group in the frequency mode. The sounding was made near the Loipeshnyun hole. These data showed that the resistivity at depth is lowered, in agreement with the position of a conductive copper-nickel layer that was previously found at a depth of 1.5 km in the hole. An important feature of these observations is also the presence of high-resistivity (greater than 10^6 Ω·m in the upper section part) crystalline rocks in the crust, which was corroborated by logging (up to $2\cdot10^6$ Ω·m).

Thus, the use of the "Zevs" antenna along with the ERS-67 truck generator with a power of 29 kW provides deep geoelectric studies virtually in all of the ore zones on the Kola Peninsula. Moreover, the use of the main 2.5 MW power installation expands the possibilities of the "Zevs" ELF antenna far beyond the borders of the Kola Peninsula, covering the entire Karelian-Kola region and adjacent territories of Finland and Norway.

5. Deep studies of the crust regard to the ionospheric effect

Deep studies of lithospheric conductivity with the "Zevs" source are the direct continuation of the sounding program with the "Khibiny" MHD generator of a power of 80 MW [Velikhov and Volkov, 1982]. The MHD soundings were used to develop the schematic integral block structure of the crustal conductivity in the northeastern part of the Baltic Shield, to construct the model for the deep structure of the lithosphere, and to estimate its conductivity to depths of 100-150 km [Zhamaletdinov, 1990].

However, the low-frequency spectrum of pulse signals from the "Khibiny" MHD source (0.05-2 Hz), which is a consequence of the low resistivity of the medium where the radiating circuit was located (the sea area around the Srednii and Rybachii peninsulas), did not allow the detailed study of the crust in an intermediate depth interval from units to tens of kilometers. Consequently, the "Zevs" source soundings are of special interest to studies of the lithosphere in the Baltic Shield.

Owing to its high power, "Zevs" provides frequency soundings at great distances from the source, under the conditions of the wave zone. This, in turn, allows the geoelectric zoning of the crust over the entire Baltic Shield for the same location of the source and gives the possibility to assess the physical and thermodynamic state of geoblocks (their porosity, fluid regime, and temperature) in various geological settings from the deep variations of electrical conductivity.

The principal advantages of the "Zevs" source, compared to the "Khibiny" circuit, are its following parameters: the location within the homogeneous Murmansk block, regular geometry (two rectangular lines grounded on the ends and 55 and 60 km long), the sinusoidal current given with a high accuracy, the possibility of precision current measurements and the environmental safety.

In 1992, the deep sounding experiment with "Zevs" was made at the southern margin of the Baltic Shield (in southern Finland), at distances from 920 to 1100 km. The measurements used a SChZ-92 digital station developed at the Geological and Polar Geophysical institutes, the Kola Research Center, Russian Academy of Sciences [Tokarev et al., 1997]. The magnetic field transducers were inductive coils, and the electric field transducers were grounded nonsymmetrical lines 300-500 m long. After the preliminarily magnification, the measured signal enters the mixer where the preliminarily filtered and magnified valid signal was multiplied by the heterodyne signal. The heterodyne frequency differed from that of the valid signal by 1 Hz. The SChZ-92 difference frequency separated by the mixer passes through the two-cascade selective amplifier and enters the 20-digit analog-to-digital converter (ADC). The discretization frequency of the ADC valid signal is 20 Hz in a dynamic range of 100 dB. After the analog-to-digital conversion, the signal enters the portable computer Note Book 486-DX through the RS-232 connector. Fig. 6 shows an example of signal detection with the "Zevs" antenna at the site of Parkano (Finland), at a distance of 920 km. One can clearly see that the signal exceeds the noise in all five components of the electromagnetic field, with average values of 0.2-0.4 nT in the magnetic field and 1.5 mV/km in the electric field. The obtained magnetic field values agree with the calculated results given in the table. The measured electric field values exceed the calculated results, since the adopted resistivity of the lower half-space (10^4 Ω·m) is substantially lower than that fixed at Parkano.

The main feature of the first experimental results was a great variance between the impedance curves of apparent resistivity ρ_T and the curves of ρ_ω in the electric field. This feature is explained by the weak attenuation of ELF waves in the Earth-ionosphere waveguide. For this reason, the commonly accepted normalization of the electric and magnetic components with respect to a homogeneous lower half-space, separated by a plane boundary from the upper half-space (air), without regard to the ionosphere, gives the resistivity values overestimated approximately by one order of magnitude. In the normalization with respect to the impedance, the ionospheric effect is compensated due to its approximately equal influence on the parameters of the electric and magnetic component propagation. Due to this value, ρ_T calculated from the effective impedance reflects the real electrical properties of the lower half-space under the wave zone conditions.

The first obtained data for the ionospheric effect on the deep sounding results were confirmed in 1993 by observations along the regional Kola-Karelia-Finland profile. The location of the profile and the observation sites are shown in Fig. 7. These sites were located dominantly within homogeneous poorly conductive blocks whose positions were chosen on the basis of the previous soundings with the "Khibiny" MHD generator [Zhamaletdinov, 1990].

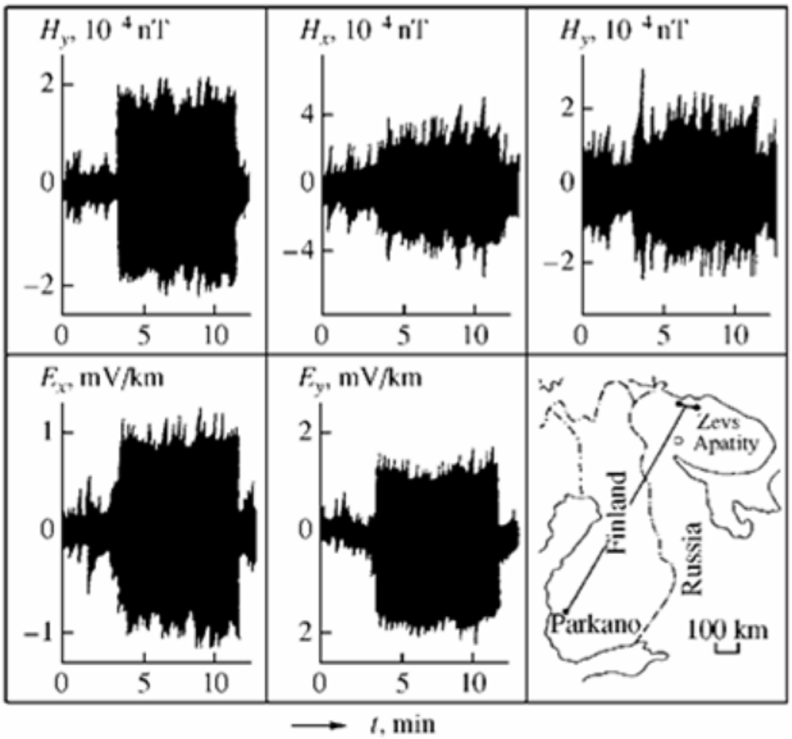

Fig. 6. Example of the five-component record of "Zevs" signals at Parkano (Finland), at a distance of 920 km from the source (on a frequency of 125 Hz).

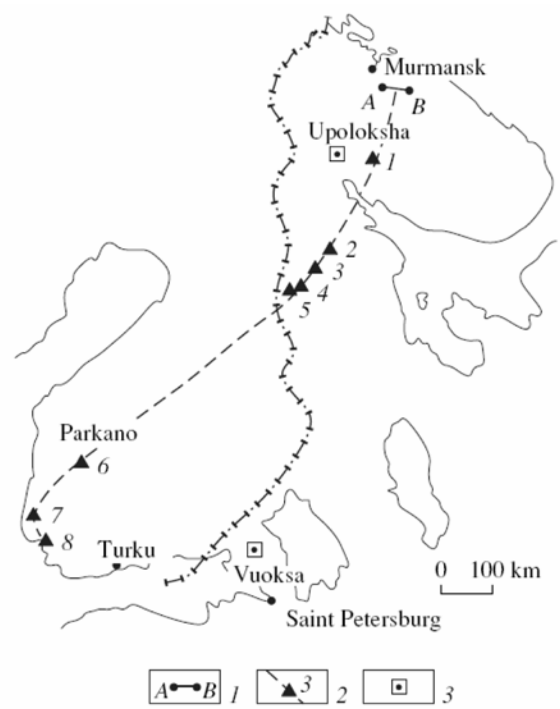

Fig. 7. Location of the "Zevs" observation profile along theKola–Karelia–Finland line. (*1*) "Zevs" source, (*2*) profile and numbers of observation points, (*3*) the geophysical research sites Upoloksha and Vuoksa.

Fig. 8 presents the results of soundings along the Kola-Karelia-Finland profile. The curves of apparent resistivity were obtained with the use of normalization by the total electric field

$$\rho_\omega^{tot} = K^{tot} E^{tot},$$

where

$$E^{tot} = \sqrt{E_x^2 + E_y^2},$$

$$K^{tot} = \frac{K_x K_y}{\sqrt{K_x^2 + K_y^2}},$$

and K_x and K_y are the geometrical coefficients for components E_x and E_y in the wave zone.

The curves of apparent resistivity ρ_t^{eff} were obtained by normalization with respect to the total impedance

$$\rho_t^{eff} = 0.2T|Z^{eff}|^2$$

where $Z^{eff} = \sqrt{E_x E_y / H_x H_y}$

The results present in Fig. 8 show a great difference between the ρ_ω^{tot} and ρ_T^{eff} curves. The former, obtained from the total electric field, on average, monotonically drop at all points. It might seem that such a behavior suggests a decrease in resistivity with depth, however, the impedance curves of apparent resistivity ρ_T^{eff} are of a totally opposite character: they ascend, with a small deviation at point *1*, where the effect of the Imandra-Varzuga conductive structure, located 10 km to the north, was probably manifested. Another important feature of the experimental data is that the ρ_{ω}^{tot} curves are shifted upward, along the resistivity axis, with distance from the source. At a distance of 920 km, ρ_{ω}^{tot} reaches exotic values of (5-7) x 10^5 Ω·m. Such behavior of the ρ_{ω}^{tot} curves is explained by the effect of the ionospheric waveguide. Due to this effect, the amplitudes of the electric and magnetic field components are eight times higher than similar amplitudes calculated for a layered half-space.

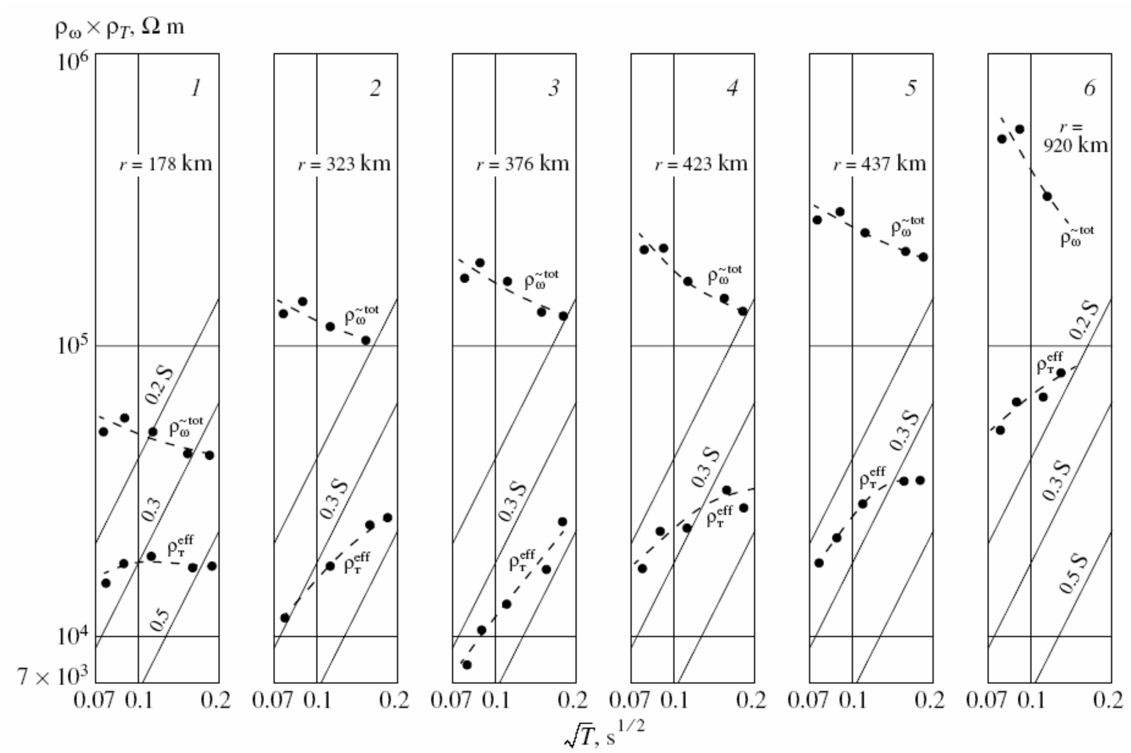

Fig. 8. Results of the soundings with the "Zevs" source along the Kola-Karelia-Finland profile (the location of points and their numbers are given in Fig. 7). ρ_{ω} is the apparent resistivity curves for the total electric field $E = \sqrt{E_x^2 + E_{yt}^2}$, and ρ_T is the same for the effective impedance $Z^{eff} = \sqrt{E_x E_y / H_x H_y}$.

This increase is quite accurately coincident with the estimates by the empirical formula accounting for the increase in the bond energy in a zero-order wave [Bernstain et al., 1974]

$$E_a / E_0 = \lambda / 4h$$

where λ is the wavelength in air (3000 km for f = 100 Hz) and h is the height of the ionosphere (about 100 km).

Analysis of the physical nature of the obtained apparent resistivity curves requires calculations of the ELF electromagnetic field in the Earth-ionosphere waveguide, taking into account the properties of the lower half-space. The theory for such calculations based on the analysis of the impedance spectrum components was developed by Makarov et al. [1993]. This theory allows us to find the field values for an arbitrary dependence of the Earth's properties and ionosphere on the radial coordinate. The solution is sought for by using the zonal and normal harmonics that are used to construct the solution in the form of a quasi-geometrical-optical series. However, this approach is applicable only at high frequencies (>1000 Hz) and for large distances from the source (greater than 1000 km).

In deep studies in the ELF range, at relatively small distances (to 2000-3000 km), the Earth's sphericity can be neglected, and the problem may be replaced by a plane one. In this case, the more accurate estimates are given by the electrodynamic method based on the calculation of the electromagnetic field components above a plane one-dimensional horizontally layered model of the lower half-space, in the presence of a plane interface (ionosphere) in the upper half-space. The ionosphere can also be represented by a layered model. The general solution to this problem was present by Boerner and West [1989]. Their equations completely describe the electromagnetic field in a one-dimensional layered medium without any approximations or assumptions. The equations were used in the development of the program of the solution to the forward problem of soundings with the "Zevs" source [Shevtsov, 1995].

In the solving algorithm, the quasistationary constraint was not introduced, and, consequently, the calculated results allowed the study of both wave and diffusive limiting cases in the electromagnetic field propagation. It was assumed that the field generation did not affect the current in the source. The Hankel transformations were calculated to a given accuracy by using the direct integration between the zeros of the Bessel functions, including the Pade approximation of the integrand [Chave, 1983]. The extension of the solution to a more general case of the spherical Earth can be obtained by expansion in spherical harmonics instead of the Bessel cylindrical functions [Whate, 1987; Sochel'nikov, 1979].

The developed program was used to calculate the field of the “Zevs” source at particular observation points. As an example, Fig. 9 shows the results calculated at the site of Parkano (r = 920 km), allowing for the effect of the ionosphere with a resistivity of 10^4 Ω·m, located at a height of 100 km. Two cases were calculated: with (ε= 0) and without (ε= 1) regard to the displacement currents. For the former case, the p curves are given with the subscript “I” (only the ionosphere influences), and for the latter case, the subscript "$i + dc$" (both the ionosphere and displacement currents influence) is used. Figure 9 also presents the experimental curves for the total electric field $\rho_\omega^{\exp}$ and effective impedance $\rho_T^{\exp}$.

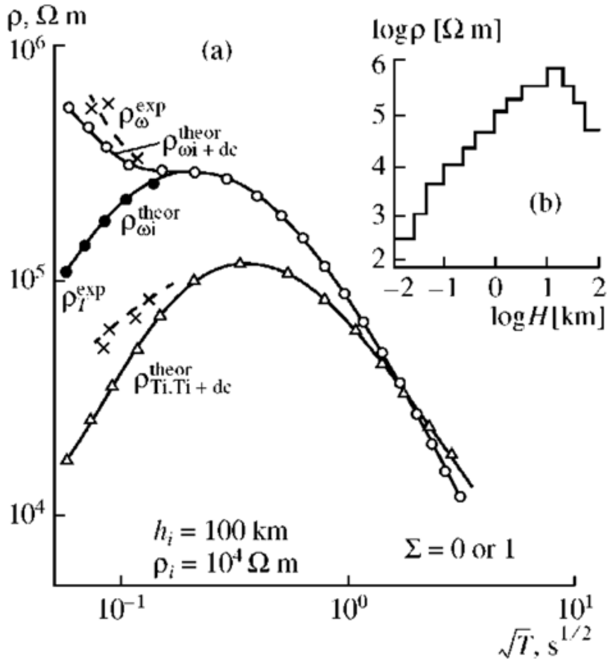

Fig. 9. (a) Theoretical and experimental curves of the apparent resistivity in the “Zevs” source field at Parkano, at a distance of 920 km from the “Zevs” source. (b) The lower half-space model accepted in the calculations. ρ_T^{theor} and $\rho_T^{\exp}$ are the theoretical apparent resistivity curves for the total impedance, respectively, ρ_ω^{theor} is the theoretical apparent resistivity curves for the total electric field $\rho_{\omega i}$ and $\rho_{\omega i+dc}$ are the curves allowing for the ionospheric effect and both the displacement currents and ionosphere, respectively; ε = 1), $\rho_\omega^{\exp}$ is the same type curves obtained experimentally. The ionosphere parameters used in the calculations: h = 100 km is the height and $\rho_i = 10^4$ Ω·m is the resistivity.

From Fig. 9, one can see that the ρ_T^{theor} impedance curves are virtually independent of the displacement current and ionospheric effect. In the wave zone, these curves adequately reflect the properties of the given lower layered half-space.

The ρ_ω curves exhibit their dependence on both the ionosphere and displacement currents. The ionospheric effect is significant already on a frequency of 1 Hz. With an increase in the frequency to 10-20 Hz, the effect is enhanced, resulting in the gradual divergence of the impedance and component curves of apparent resistivity. For higher frequencies of 20 to 500 Hz, the ionospheric influence is stabilized and leads to the parallel shift of the ρ_T^{theor} and ρ_ω curves (Fig. 9). The displacement current effect is observed only in the left high-frequency branches of the curves and is manifested in their abruptly ascending shape for frequencies of 80 to 100 Hz and higher. Such behavior of the ρ_ω^{theor} curves agrees with that of the experimental $\rho_\omega^{\exp}$ curve.

The above analysis of the theoretical and experimental results with the “Zevs” source shows that these results can be brought into agreement only by allowing for the displacement current effect, along with the ionospheric effect. Such a conclusion is at variance with the usual opinion that, for slowly varying fields, it is possible to neglect the displacement current and to restrict ourselves to a quasistationary model described by the diffusion equations. In this case, the quasistationary condition is determined by the inequality $\omega\varepsilon << \sigma,$ where ε= 8.84 x 10^{-12} F/m. It directly follows that, for $\sigma = 10^{-4}$ Ω·m^{-1}, the quasistationary condition holds true in a frequency range from zero to 10^6-10^7 Hz. However, in this case, the displacement currents in air are not automatically taken into account. The actually observed effect of displacement currents on super low frequencies is explained by the fact that a finite velocity of electromagnetic field propagation from the source to the receiver must be included in the interpretation of deep soundings [Vanyan, 1997]. Then, the quasi-stationary constraint is added by the condition $r << \lambda_0/2\pi$, where r is the source-receiver distance and X_0 is the wavelength in air, $\lambda_0 = \dfrac{2\pi}{\omega\sqrt{\varepsilon_0\mu_0}}$. The constraint on the wavelength in air gives rise to the fact that, for example, for a separation of r = 500 km, the quasistationary condition holds true only in a range from zero to 100 Hz.

In total, the experimental and theoretical curves in Fig. 9 are in agreement with each other. In order to achieve complete agreement, additional calculations are required, with the use of more realistic values of relative permeability ε and more accurate data on the electric conductivity of the Earth and ionosphere. Given the conductivity of the Earth, the parameters of the ionosphere can be fitted more accurately and *vice versa.* However, such a problem is beyond the scope of this paper. In studying the conductivity of the Earth, we can restrict ourselves to the results of the impedance processing of data for the distances exceeding the wavelength in the Earth ($r >> \sqrt{10\rho T}$). This condition holds true over the entire ELF range, at distances greater than 300 km, for an average medium resistivity of 10^5 Ω·m.

The summary diagram of the results of soundings with the "Zevs" source (impedance curves) is present in Fig. 10. The data of deep soundings with natural and controlled sources on the Baltic Shield are also given in Fig. 10. All these results were selected from measurements on a fortiori homogeneous, poorly conductive blocks of the crust. It is remarkable that the ρ_T^{eff} impedance curves, obtained with the "Zevs" source, are grouped in a band covering the lower part of the hatched zone of probable ρ_ω values for the Karelia-Kola region, the part found from the frequency and MHD soundings and referred to as the "normal" section. These results contrast with the ρ_T distributions in Fig. 10, obtained with the help of natural sources in the Russian territory of the Baltic Shield [Vanyan et al.,1980; Kovtun et al., 1986] and in central Finland [Korja, 1990].

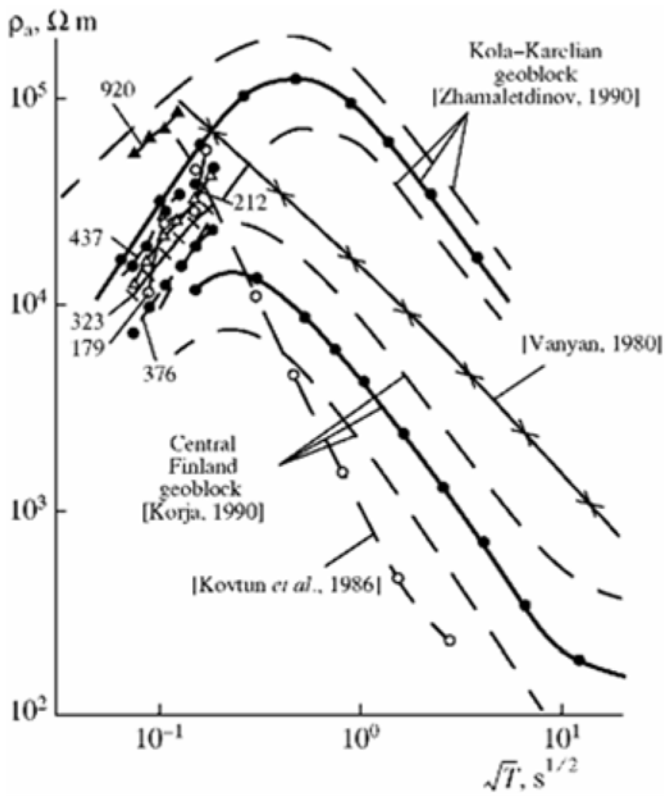

Fig. 10. Summary diagram of the normal apparent resistivity curves for the Baltic Shield from data obtained by various authors and the comparison with the results of "Zevs" antenna soundings at different distances from the antenna. Digits at the curves are the distances (in km) from the antenna. The ρ_ω are normalized with respect to the effective input impedance.

Many authors believed that the use of grounded (galvanic) electromagnetic generators in the installations of power lines, Khibiny MHD source, "Zevs" antenna, etc. is one of the causes for the observed differences in the interpretations of soundings with natural and controlled sources. In this case, along with the inductive component, the original field contains the galvanic mode with the vertical electric component, whose role is enhanced as the frequency drops and the separation decreases. Under conditions of the K-type section, the galvanic mode is weakly sensitive to the lower conductive layer, since the intermediate poorly conductive layer hinders the penetration of current into the lower half-space, and the current spreads mainly in the upper layer.

In order to analyze the resulting situation, we calculated the electromagnetic field of the "Zevs" antenna along the route oriented at an angle of 60° to the dipole axis, corresponding to experimental data (Fig. 7), for two geoelectrical models: the K-type normal section with a poorly conductive layer (Fig. 11e, model 1) and the same section containing, however, an intermediate conductive layer at a depth of 10 km (Fig. 11e, model 2). The longitudinal conductivity of the layer was set at 250 S, and its thickness was 10 km, which corresponds to data for the Murmansk block [Kovtun et al., 1986]. The results of the calculations and the accepted models are present in Fig. 11. The ionospheric and displacement current effects were taken into account in a frequency range of 0.01 to 1000 Hz, for the separations ranging from 50 to 800 km.

The calculated results for model 1, with the normalization relative to the impedance and electric field E_x parallel to power line AB, are shown in Figs. 11a and 11b, respectively. The right ascending branches of the impedance curves reflect the decreased influence of the wave zone with an increase in the separation. The ρ_T curves almost coalesce at separations of 600-800 km. The doubled thick line in Fig. 11a is the averaged experimental data of soundings with the "Zevs" source for separations of 300-900 km. These data are not beyond the bounds of the left ascending curve caused by the resistivity increased with depth.

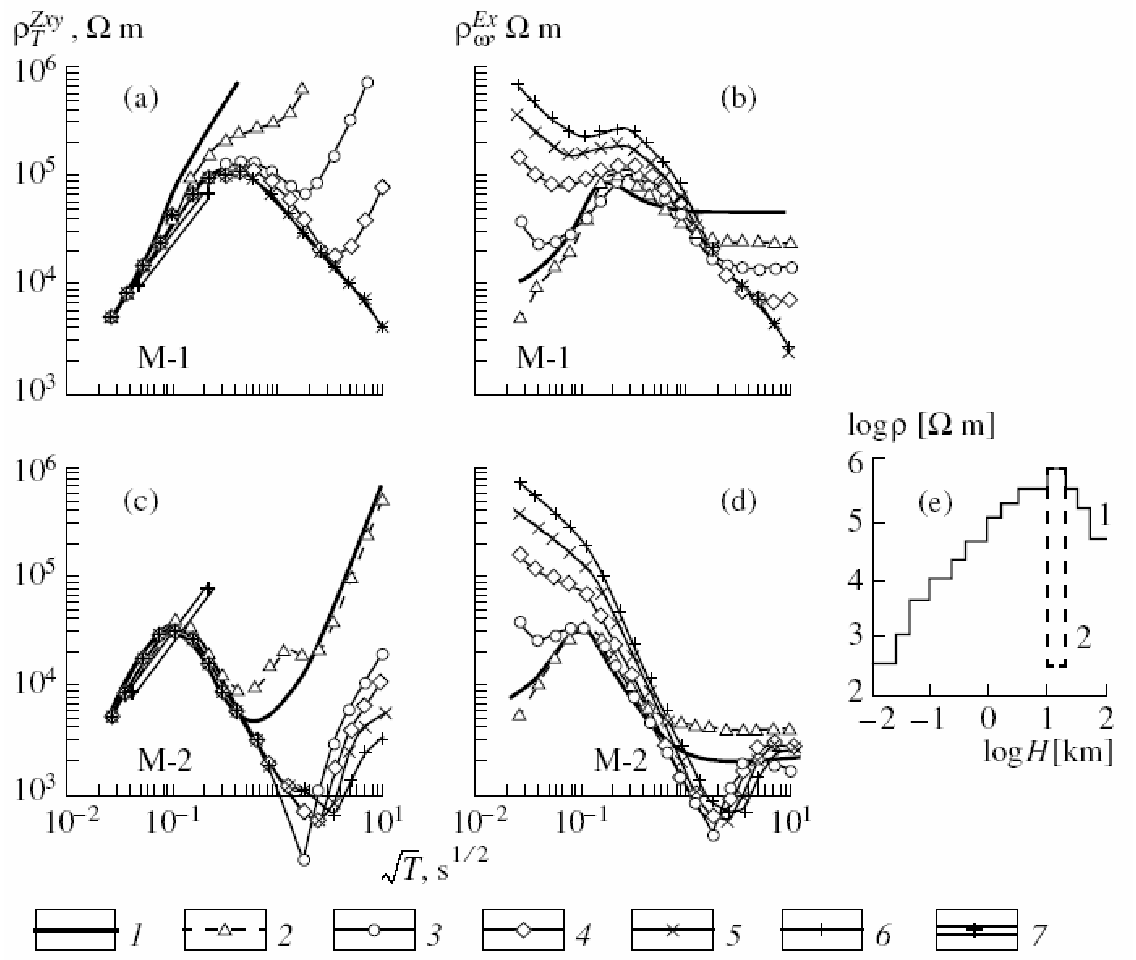

Fig. 11. Comparison of the experimental data from deep soundings in the "Zevs" antenna ELF field with theoretical results for two section models. (a) and (b) Calculations for the normal gradient-layered K-type model (model 1 in Fig. 11e). (c) and (d) Calculations for the normal model with an intermediate conductive layer at a depth of 10 km (model 2 in Fig. 11e). (a) and (c) Theoretical curves with normalization with respect to the input impedance; (b) and (d) the same curves with normalization with respect to electric field E_x parallel to power line AB. (e) Models 1 and 2. Notation: *(1)-(6)* theoretical curves for different distances between the "Zevs" antenna and reception points: *1*, 5; *2*, 100; *3*, 200; *4*, 400; *5*, 600; and *6*, 600; *(7)* average position of the generalized apparent resistivity curve based on the input impedance, for the "Zevs" source and separations from 300 to 900 km (from experimental data).

The ρ_ω curves for electrical component E_x reflect the joint effect of the ionosphere, displacement currents, and varying wave stage. One can see that the galvanic mode has the prevailing effect for a separation of 50 km: the ρ_ω curve is of the two-layer $(\rho_2 > \rho_1)$ type, reaching the direct current at frequencies of 50-100 Hz. With a further increase in the separation, the right ρ_ω branches undistorted by the ionosphere and displacement currents are virtually coincident with the impedance ρ_T curves.

For the model with an intermediate conductive layer at a depth of 10 km, the apparent resistivity curves change their shape (Figs. 11c, 11d). For all the separations, we see the abruptly ascending impedance curves already at frequencies of 80-100 Hz, suggesting the presence of the conductive layer at the 10-km depth (Fig. 11c). A similar picture is observed for the apparent resistivity curves calculated for electrical component E_x, ρ_ω.

The experimental data of the "Zevs" source, shown in Fig. 11c, are close to the theoretical curves and are contradictory to the proposal on the possible existence of the conductive layer at a depth of 10 km. The obtained electrical section exhibits the natural pattern of an increased resistivity in the upper crust with the increasing depth of sounding up to 10-20 km. On the order of magnitude, the resistivity values agree with laboratory data and can be used to study the further features in the physical state of the crust. For the more complete solution to the problem, it is desirable to expand the frequency range in the direction of low frequencies, at least, up to the maximum on the apparent resistivity curve and its further drop, i.e., up to a frequency of about 1 Hz.

Thus, the tests of the "Zevs" power installation in the on-duty regime showed that such deep geoelectrical studies can be fundamentally performed in the almost entire Baltic Shield. The portable frequency sounding equipment developed at the Geological and Polar Geophysical Institutes, Kola Research Center, can be used in these measurements.

6. Other promising research with the "Zevs" source

The large distance over which the signals from "Zevs" propagate and their low-frequency spectrum determine wide possibilities of its use in various fields of geophysics. Below, we list some of the possible directions of research, taking into account that this paper is an overview and we are interested in a wide cooperation with various potential participants of future works.

Electromagnetic Monitoring for Earthquake Prediction Problems.

Of the various possible uses of the "Zevs" source in the national economy, the most interesting problem is the electromagnetic monitoring of the Earth's stress state with the purpose of earthquake prediction.

To this time, generally accepted criterions for earthquake prediction do not exist, and all the efforts to solve this problem end in conclusions on the necessity to apply a multidisciplinary geological-geophysical approach based on several methods. Of them, seismology and geoelectrics are most often used.

The "Zevs" installation itself is located in a low-seismicity zone. The nearest objects of interest for seismic safety monitoring are the Kola atomic power station (APS) located in a zone of the Kandalaksha graben influence and the Lesnoi Bor APS in the Leningrad region. More remote areas (Fig. 2) are in the zone of weak "Zevs" influence (Fig. 2). Nevertheless, observations suggest that the *«Zevs»* source signals can be convincingly detected in the greater part of the CIS seismic zones. The apparatus of the AKF (autocorrelative function) series developed at the Research Institute of the Crust, Saint Petersburg University, satisfies the necessary requirements.

In December of 1995, by the initiative of the Ministry of Emergency Situations (MES), this apparatus was used in tests at the Caucasus Mineral'nye Vody seismic prediction site, at a distance of 2700 km from the "Zevs" antenna [Saraev et al., 1997]. In spite of unfavorable winter conditions and a high level of noise, quite satisfactory results were obtained in the recurrence of data from cycle to cycle. The average ELF "Zevs" signal relative to the natural electromagnetic field at frequencies of 125 and 166.6 Hz ranged from 5 to 11 dB. The relative differences in the horizontal impedance modulus at these frequencies between the morning and evening measurements did not exceed 2.1-2.6%.

Taking into account that the average value of the p_a deviations for earthquakes with a magnitude of 5-6 is 16-20% [Barsukov and Sorokin, 1973], it can be believed that the obtained results confirm the suitability of the "Zevs" source for geophysical monitoring.

In the circle of the earthquake prediction problems of interest for the MES, it is necessary to clearly formulate the sphere of the application of the "Zevs" source and its priority value compared to other methods applied in this field.

The seismic risk zones are usually located in the regions with a pronounced horizontal electrical inhomogeneity of the crust (in fault zones, shear and thrust slip zones, the contacts between various crustal blocks, and along fold geosyncline belts or island arc systems). Along with the variation in the overall resistivity of the crust in the source zone, the earthquake preparation is accompanied by variations in the relationship between the electrical inhomogeneity elements of the medium. For example, the compressive stresses are concentrated along a fault controlling the source zone position and, at the moment of their discharge (earthquake), are converted into shear stresses.

The fluid regime of the crust and, correspondingly, its electrical conductivity change during this conversion. Furthermore, the overall conductivity may change minimally, while the orientation of the electrical inhomogeneity axes may vary significantly due to the movement of fluids from the compressive zones to the extension ones. Finally, these variations must lead to the rotation of the total vectors of electric and magnetic fields through an angle. In this case, the decisive attraction can be given to the application of a controlled source with a given polarization direction of the original field. The phase measurements between the mutually orthogonal components of the same kind, i.e., $\Delta\varphi E_x/E_y$ and $\Delta\varphi H_x/H_y$, may be put in the forefront.

The physical-geological model for earthquake prediction in the ELF range can be based on the hypothesis that the major events preceding an earthquake proceed due to water coming into the fractures opening up before the earthquake in the fluid-saturated upper crust [Barsukov and Sorokin, 1973; Mogi, 1988]. The theory of earthquake precursors for this case is developed in the framework of the dilatance-diffusion model describing changes in the fluid regime of the uppermost crust (200-500 m) accessible for the ELF measurements even in rocks with a fairly high conductivity (30 100 Q m). In this case, the depth of the ELF sources remains sufficiently great to avoid the prevailing influence of the seasonal variations in rock conductivity.

Ecology.

A set of environmental problems is related to electromagnetic monitoring. Here, the field of the "Zevs" source may be used in searching for the monolithic crustal blocks suitable for the burial of radioactive waste and for aseismic building. The experience of works with the Khibiny MHD generator showed that these problems are most reliably solved in the field of a unified fixed source. In this case, it is possible to reveal the ancient monolithic and poorly conductive crustal blocks with their roots escaping in the protobasement strata and to distinguish them from the relatively young and also poorly conductive dome-shaped granitoid blocks "floating" in the supracrustal substrate and, consequently, being more seismically dangerous.

Wireless Communication.

The problem of wireless communication is topical because it is necessary to transmit messages to deep galleries in the case of emergency situations, when all other communication means are disrupted. In this direction, the ELF antenna has certain advantages, since its frequency range enables us to reliably detect the emitted signals at great depths in the crust, up to 1 km and deeper, in the entire Karelia-Kola region. An exception is the case when the galleries are in strata of highly conductive rocks, for example, in sulfide-carboniferous schists or sedimentary rocks of clay type. These cases require preliminary study on the conditions for ELF signal propagation.

Examination of the Barents Sea Shelf.

The location of the “Zevs” ELF antenna near the Barents Sea shoreline allows us to propose a promising problem on using the radiated electromagnetic field in measuring the electrical conductivity of the bottom sediments in the Barents Sea shelf, with the purpose of predicting the oil-bearing fields in common with other geophysical methods. This problem needs a model for electromagnetic wave propagation in the sea bottom and for field energy scatter in sea water, described like the scatter in the ionospheric waveguide. The preliminary calculations intended to test this model showed that the optimum approach may be provided by measurements for the location of the receiving electrical antenna on the seafloor. In this case, a gain in the amplitude may reach two orders of magnitude, compared to the measurements on the sea surface. Moreover, the distance of detection may be up to several thousands of kilometers, under conditions of high-resistance bottom rocks, which provides the weak attenuation of the ELF field.

Conclusion.

Thus, the studies with the “Zevs” ELF radio transmitter open up wide possibilities for the further development of this system, including the creation of a multi-disciplinary installation capable of solving the forward communication problem along with problems of applied and basic geophysics, such as deep soundings, seismic prediction, and study of the wave properties of the ionosphere. A specific feature of the installation is the possibility of simultaneously solving various problems in various regions, following a synchronous and coordinated program of “Zevs” source starting. The profitability of the program directly depends on the number of users. However, the practical use of the source must be preceded by a prolonged stage of theoretical and experimental investigations, and this paper is only the very beginning of this process.

In conclusion, it should be noted that all of the studies on the creation of the “Zevs” installation were carried out by the Russian Institute for Power Radio Engineering, with the participation of a number of other institutions, of which a major role was played by the Institute of the Crust and the Institute of Radio Physics (Saint Petersburg University), as well as by the Nizhni Novgorod Institute of Radio Physics and the Research Institute of Direct Current, Geological Institute of the Kola Research Center, Russian Academy of Sciences.

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