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Cryosphere of the earth and its influence on electromagnetic processes in seismoactive mountainous areas

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Abstract

The purpose of this paper is to present a detailed physical description and classification of electrical properties, construction and structure of the cryolitozone at the depth of skin-layer in VLF range for Aldan plateau, central part of the Yakutia and tundra regions not far from the Arctic Ocean. Electrical characteristics of the regions studied are typical for the cryolitozone. The frequency dispersion of some types of permafrost zones is experimentally studied. It is then shown that the frequency dispersion of the electric resistance of the layer of frozen friable sediments over the frequency from direct current to VLF–MF ranges is a peculiarity of electrical properties of the cryolitozone. A complex interpretation of the data of radioimpedance and electric soundings for permafrost rocks is carried out on the basis of developed automated numerical methods of direct and inverse problems for the radioimpedance sounding. It is determined that geoelectrical sections with the type of K ($\rho_1 < \rho_2 > \rho_3$) and the type of Q ($\rho_1 > \rho_2 > \rho_3$) are most typical for sediment rocks of the cryolitozone at the depth of 100 m of the Northern-East part of Russia. Geoelectrical section A ($\rho_1 < \rho_2 < \rho_3$) is the basic for ancient crystal rocks of the Aldan shield. Electrical properties of the cryolitozone are changed appropriately in space and in time and depend on the complex of the crystal and sediment rocks. The surface impedance shows inductive and capacitive nature and is changed in a wide range from minimum for saline lands to maximum for granitoids.

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Keywords: Cryolitozone; Surface impedance; Frequency dispersion; Attenuation function

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1. Introduction

Permafrost rocks (cryosphere of the Earth) are widely distributed in areas with subpolar and cold-temperate climate. They constitute 24% of all lands of the Earth, i.e. more than 35 million km^2. The thickness of the layer of permafrost rocks grows from the south to the north from several meters up to 1500 m and more. Investigations of electromagnetic processes and of the phenomena in the cryosphere are carried out in a number of countries including Russia, Canada and USA. However, in seismoelectromagnetics works there are no data at all on the influence of the physical characteristics of the cryogenic environment on the processes of excitation and propagation of electromagnetic waves. It is necessary to note that the seismoactive area of Alaska and the north of Canada, northeast of Eurasia, high mountains of Pamir, Tien Shan, the Himalaya and the Andes belong to the cryosphere of the Earth. Thus, cryogenic areas with very low electrical conductivity are one of the most poorly investigated objects in seismoelectromagnetics. Resistivity of a permafrost at direct current reaches 10^4–2.5×10^6 Ω m. As a whole, very few works are devoted to electromagnetic properties of cryolitozone. We shall also notice that monitoring of radon in cryolitozone

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for the purpose of the forecast of earthquakes is not effective because of the strong shielding influence of a layer of permafrost rocks with thickness up to 1500 m.

In this paper we present the detailed physical description and classification of electric properties, construction and structures of the cryolitozone for northeast of Eurasia (Aldan plateau, the central Yakutia and tundra areas near the coast of the Arctic ocean). As a result of experiments it is established that electric properties of the cryolitozone change regularly with space and time and they depend on the complexities of crystal and sedimentary rocks. Electric characteristics of the regions investigated are typical for the cryolitozone.

2. Frequency dispersion

The cryolitozone frequency dispersion is experimentally studied. It is established that the main feature of the electric properties of cryolitozone is the frequency dispersion of electric resistance of a layer of frozen loose sediments (FLS) in the frequency from direct current to VLF–MF ranges. For a geoelectric section (GES) containing "low-temperature" frozen loose sediments, the distinction of their electric resistivity (ER) between direct and alternating currents is established. ER values restored from solving the inverse problem on radioimpedance sounding (REMS) data are found to be less than those estimated through vertical electric sounding (VES) by a factor of 2.5–10. We present the physical interpretation of the obtained results for permafrost rocks with taking into account the influence of conducting inclusions on the multiphase heterogeneous medium. The discrepancy of values of impedance measured through the REMS and computed on VES data is due to the distinction of ER between direct and alternating currents. Attenuation of electromagnetic wave during its propagation in the two-component medium is determined by the electric parameters (ρ and ε) in each of the medium. Then in case of prevalence of conductivity currents in each medium, the effective resistance of such a two-component medium is frequency independent and it is calculated by the following formula (Melchinov, 1999):

$$\rho = \left[\frac{v^2}{\rho_1} + \frac{(1-v)^2}{\rho_2} + 2v(1-v)\sqrt{\frac{1}{\rho_1\rho_2}}\right]^{-1}$$

where ρ_1 is the resistivity of isolated conducting inclusions, ρ_2 is the resistivity of the containing frozen medium, and v is a fraction of volume of inclusions in the medium. In the literature the fraction of non-frozen water at negative temperatures can contain from 1% up to 35% of the volume, depending on the kind of rocks (Frolov, 1998). Model calculations have shown that effective resistance of the two-component medium with $\rho_2 = 10{,}000\ \Omega\,\mathrm{m}$, $\rho_1 = 10\ \Omega\,\mathrm{m}$ and $v = 0.05$ decreases by more than two times in comparison with the ER of mineral skeleton. Presence of conducting inclusions can considerably influence the attenuation of radiowaves, while on direct current they do not participate in carrying an electric current and the ER of a two-component medium for direct current is almost equal to ρ_2.

Thus the distinction of ER of frozen rocks between direct and alternating currents arises from the influence of isolated conducting inclusions, because at direct current carriers of charges in conducting inclusions do not participate in carrying a current. In a layer of frozen loose sediments, loose- and solid-bound water can be such inclusions. Model calculations of effective resistance of the two-component medium and of radio wave attenuation have shown that the effective resistance is lower by 2.1–13.3 times than in a mineral skeleton in dependence on the content of water, and it remains to be constant in the frequency range of 10–1000 kHz.

Good convergence between values of surface impedance computed on VES data and measured values of the horizontal-layered underlying medium is obtained at the sites of deposition "high-temperature" frozen rocks and in case of weak contrast of layers of GES for salines, loams and for all types of crystal rocks. Thus we confirm the absence of frequency dispersion of electric properties of the frozen rocks which are taking place in condition, close to thawed and thawed rocks.

The ascertainment of frequency dispersion of permafrost puts forward an actual problem of electromagnetic wave propagation in the media with dispersion, and also a problem of research of dispersion characteristics of various types of cryosphere from direct current up to tens of MHz.

3. Surface impedance

The analysis of numerous measurements of surface impedance of various types of cryogenic rocks (more than 2000 measurements of $|\delta|$ and of φ_δ in 16–864 kHz range) has shown that the module of impedance changes within the limits of 0.006–0.32. The impedance shows inductive and capacitive nature and it changes over a wide range from minimal for salines up to maximum for granitoids (Bashkuev, 1996). The variation of φ_δ is in the range of $-82^\circ \sim +16^\circ$ i.e. from strong-inductive up to loose-capacitive impedances that is not marked earlier in none of the regions of the Earth. Table 1 presents the minimum–maximum and average values of $|\delta|$, φ_δ, and effective resistance ρ, from the results of investigations in the central Yakutia.

Features of frequency dependence of surface impedance and geoelectric section are revealed for each type of rocks. In Table 2 we present maximum and average values of impedance for different types of sedimentary rocks at three frequencies of VLF, LF and MF ranges of radiowaves.

Limits of variations of the module and phase of impedance are given in the numerator in Table 2, and average values are given in the denominator. For example, $|\delta|$ values for salines almost do not depend on frequency because of the sharp contrast ER of thawed and frozen layers. The phase of impedance with growth of frequency is shifted in the area of loose-inductive values and then in the bottom

Table 1
Frequency dependence of impedance ($|\delta|$, φ_δ) and effective resistance φ

f, kHz	$\lvert\delta\rvert$				φ_δ°				ρ, Ω m			N
	min	max	Average	$\frac{\lvert\delta\rvert_{\max}}{\lvert\delta\rvert_{\min}}$	min	max	Average	$\Delta\varphi_\delta$	min	max	Average	
16.2	0.006	0.052	0.018	8.7	−79	−33	−45	58	40	3100	530	81
17.4	0.006	0.083	0.019	13.4	−81	−25	−51	56	48	4800	560	69
50	0.010	0.098	0.035	9.8	−78	−15	−61	63	52	3500	690	76
171	0.008	0.21	0.065	25.8	−61	+9	−32	70	9	7300	810	165
290	0.014	0.25	0.079	17.8	−64	+7	−28	71	15	7700	770	135
549	0.018	0.29	0.1	16.2	−61	+16	−20	77	12	10,300	1800	140
864	0.039	0.32	0.115	8.2	−53	+13	−16	66	41	15,300	1200	68

Table 2
Frequency dependence of the module and phase of impedance for different types of rocks

Types of rocks	Frequency, kHz					
	17.4		171		549	
	$\lvert\delta\rvert$	φ_δ°	$\lvert\delta\rvert$	φ_δ°	$\lvert\delta\rvert$	φ_δ°
Sands	$\frac{0.013-0.038}{0.016}$	$\frac{-25\sim-81}{-55}$	$\frac{0.018-0.21}{0.076}$	$\frac{-5\sim-67}{-34}$	$\frac{0.029-0.29}{0.12}$	$\frac{+10\sim-61}{-23}$
Loams	$\frac{0.011-0.037}{0.021}$	$\frac{-26\sim-78}{-51}$	$\frac{0.031-0.14}{0.066}$	$\frac{-9\sim-58}{-32}$	$\frac{0.023-0.29}{0.1}$	$\frac{+16\sim-42}{-17}$
Salines	$\frac{0.01-0.068}{0.017}$	$\frac{-31\sim-62}{-44}$	$\frac{0.012-0.1}{0.033}$	$\frac{-8\sim-53}{-34}$	$\frac{0.018-0.14}{0.044}$	$\frac{+11\sim-41}{-20}$

The numerator indicates the range of variation, while the denominator, the average value.

Table 3
Frequency dependence of the impedance ($|\delta|$ and φ_δ) for three types of crystal rocks

Age of rocks	Frequency, kHz					
	17.4		171		666	
	$\lvert\delta\rvert$	φ_δ°	$\lvert\delta\rvert$	φ_δ°	$\lvert\delta\rvert$	φ_δ°
Archey	$\frac{0.009-0.076}{0.04}$	$\frac{-21\sim-62}{-40}$	$\frac{0.031-0.24}{0.11}$	$\frac{+3\sim-60}{-29}$	$\frac{0.069-0.25}{0.14}$	$\frac{-17\sim-57}{-29}$
Cambria	$\frac{0.0059-0.074}{0.026}$	$\frac{-24\sim-61}{-44}$	$\frac{0.014-0.11}{0.05}$	$\frac{-4\sim-51}{-26}$	$\frac{0.012-0.2}{0.08}$	$\frac{+3\sim-45}{-18}$
Proterozoy	$\frac{0.012-0.077}{0.02}$	$\frac{-26\sim-67}{-42}$	$\frac{0.031-0.026}{0.08}$	$\frac{-12\sim-59}{-33}$	$\frac{0.014-0.26}{0.11}$	$\frac{-9\sim-69}{-39}$

part of MF band (300–900 kHz) back to strong-inductive impedances.

The highest values of $|\delta|$ in VLF band is found on crystal rocks of Aldan plateau in the south of which the Chulman hollow with earthquakes up to $M = 7$ is located. Here φ_δ in most of cases in absolute value is less than 45° in all ranges of frequencies that corresponds to the geoelectric section of type $\rho_1 < \rho_2 < \rho_3$. In Table 3 limiting and average values of $|\delta|$ and φ_δ are given for three types of crystal rocks in VLF–MF bands.

The minimal values of the module of surface impedance are characteristic for cambrian and proterozoic rocks, and maximal values are obtained for archean granitoids. The significant differentiation of ER between sedimentary and crystal rocks is established. Good coincidence of electric borders with geological borders for various complexes of rocks (granitoids, cambrian and jurassic sediments etc.) is revealed. For the same type of crystal and sedimentary rocks statistical distribution of effective resistance $\rho_\sim$ follows the lognormal law. Geoelectric sections at the depth of a skin-layer in VLF band (300–500 m) contain very often from 3 up to 5 layers in the vertical electric sounding data in the territory studied.

4. Geoelectrical section

We have carried out a complex interpretation of the data of radioimpedance and electric soundings for permafrost rocks of the Central and Northern Yakutia, Aldan plateau and Vitim plateau on the basis of developed automated numerical methods for decision of direct and inverse problems of radioimpedance sounding. The software package "Impedance" created on the basis of A.N. Tikhonov's regularization method is used for the interpretation of radioimpedance soundings (Angarkhaeva et al., 1997). It is determined that geoelectrical sections of the K-type ($\rho_1 < \rho_2 > \rho_3$) and of the Q-type ($\rho_1 > \rho_2 > \rho_3$) are most typical for sedimentary rocks of the cryolitozone at the

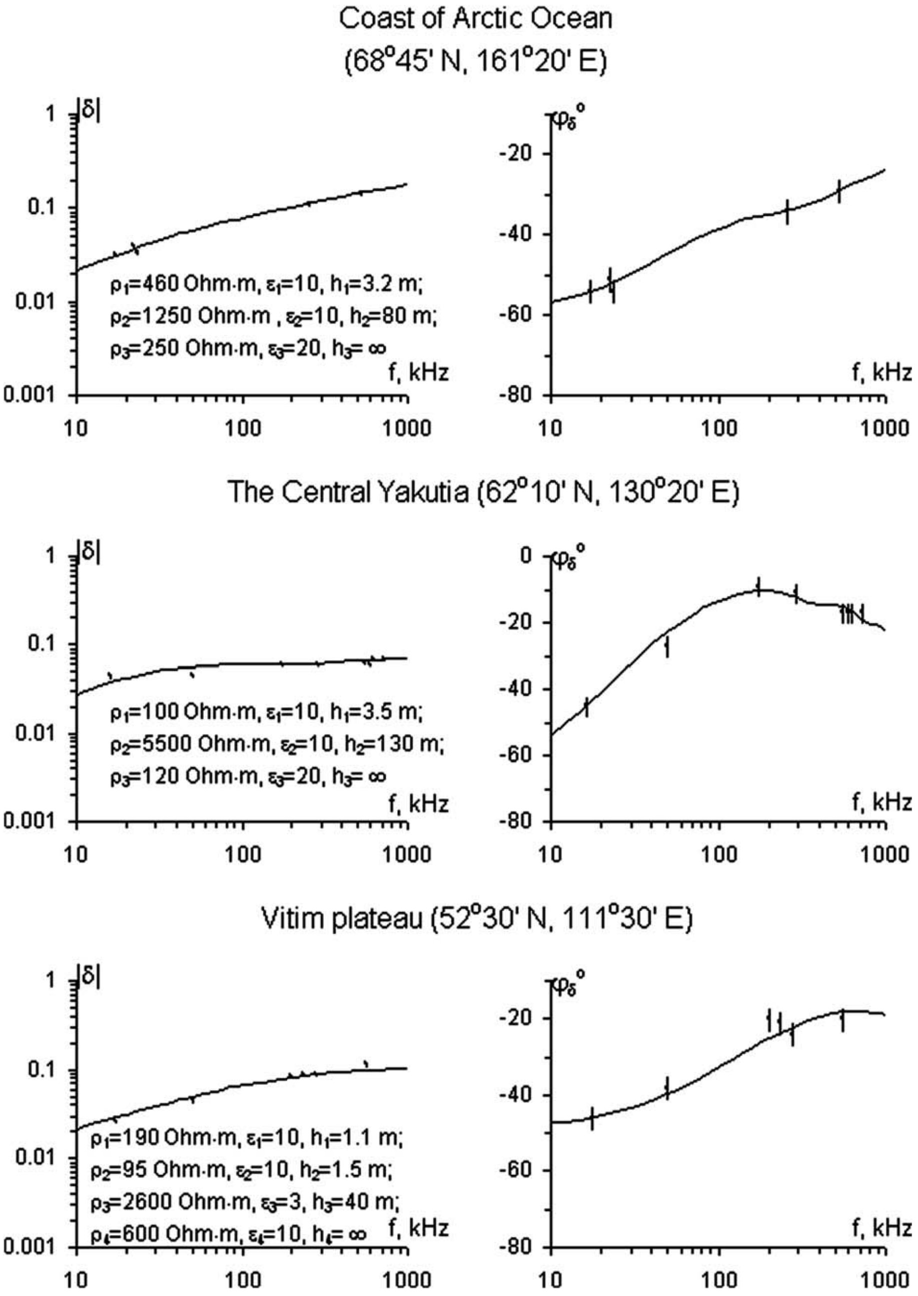

Fig. 1. Frequency dependences of surface impedance and geoelectrical section of permafrost rocks at various latitudes, h_i ($i = 1$–4) is the layer thickness.

depth of 1000 m. A-type geoelectrical section ($\rho_1 < \rho_2 < \rho_3$) is basic for ancient crystal rocks of the Aldan shield. This fact means that ER increases with the depth from a few hundreds Ω m up to tens of thousands Ω m (see Figs. 1 and 2). The technique of geoelectrical mapping of cryolitozone is provided according to the radioimpedance measurements (Bashkuev et al., 2003), and we generate prediction map of geoelectrical sections of Northeast of Eurasia.

5. Electromagnetic field

Modeling of processes of propagation of electromagnetic waves in the cryolitozone was carried out for mountainous seismoactive areas of the northern part of Eurasia. The source is a vertical electric dipole that is situated on the Earth and emits radio waves propagating along the spherical surface. The observed LF–MF vertical component of electrical field E_z is given as $E_z = W \cdot E_0$, where E_0 is the field in free space and W is an attenuation function associated with underlying medium properties. The algorithm and the program of calculation of the attenuation function of the field propagated over geometrically and electrically inhomogeneous radio paths by the method of generalized Feinberg's integral equation are developed (Dembelov and Bashkuev, 2005). Ott published an alternative Feinberg's integral equation and its numerical solution (Ott, 1992). The radio path is considered to be

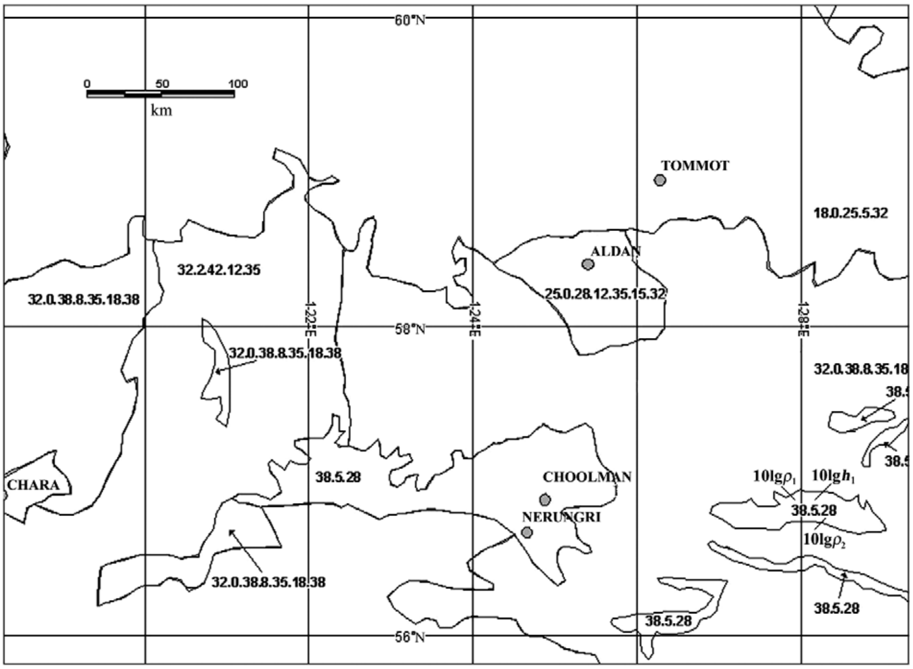

Fig. 2. The fragment of the map of geoelectrical sections of Southern Yakutia. The figures in the map are explained as follows. Please look at the figure in the right down part (38.5.28), the first figure (38) is ρ_1 (in the form of $10\lg\rho_1$), the second, h_1 (in the form of $10\lg h_1$) and the third, ρ_2 (in $10\lg\rho_2$). When you have five figures, they consist of ρ_1, h_1, ρ_2, h_2, and ρ_3.

sectional-homogeneous. Feinberg's integral equation is one-dimensional and it takes into account inhomogeneities that are along the radio path. The attenuation function is written in the following electrically inhomogeneous integral form (Feinberg, 1959):

$$W(D) = W_0(D) + \mathrm{i}\sqrt{\frac{\mathrm{i}kD}{2\pi}}\int_0^D [\delta - \delta_0]\frac{W(x)W_0(D-x)}{\sqrt{x(D-x)}}\,\mathrm{d}x. \tag{1}$$

Here δ is the current surface impedance, $k = 2\pi/\lambda$, λ is the wavelength, x is the distance between the source and current integration point, and D is the distance between the source and receiver along the Earth's surface. The function $W_0(D)$ is calculated by Fock's formula with arbitrary impedance δ_0 (Fock, 1965; Wait, 1962),

$$W_0(x_0,y,q) = \sqrt{\mathrm{i}\pi x_0}\sum_{s=1}^{\infty}\frac{\mathrm{e}^{\mathrm{i}x_0 t_s}}{t_s - q^2}\,\frac{w(t_s - y)}{w(t_s)}. \tag{2}$$

Here $x_0 = \frac{D}{a}\left(\frac{ka}{2}\right)^{\frac{1}{3}}$, $y = \left(\frac{2}{ka}\right)^{\frac{1}{3}}kh$, $q = \mathrm{i}\delta_0\left(\frac{ka}{2}\right)^{\frac{1}{3}}$, where a is the Earth's radius, and h is the receiver height. Parameters t_s are roots of the transcendental equation $w'(t) - qw(t) = 0$ that takes into account the approximate boundary condition for vertical component E_z, $w(t)$ is the Airy function determined by the Airy equation of $w''(t) - tw(t) = 0$ and $w'(t)$ is its derivative.

The integral equation (1) is well suited for calculating the attenuation function for lengthy and low conducting electrically inhomogeneous paths that are within seismoactive mountainous areas of the Earth's cryosphere. Fig. 3 shows the experimental data (by rectangles) and the corresponding calculations of the module and argument of the attenuation function W at a frequency of 576 kHz. Calculations were carried out with the help of Hufford's (Hufford, 1952) and Feinberg's integral equations. Calculations made

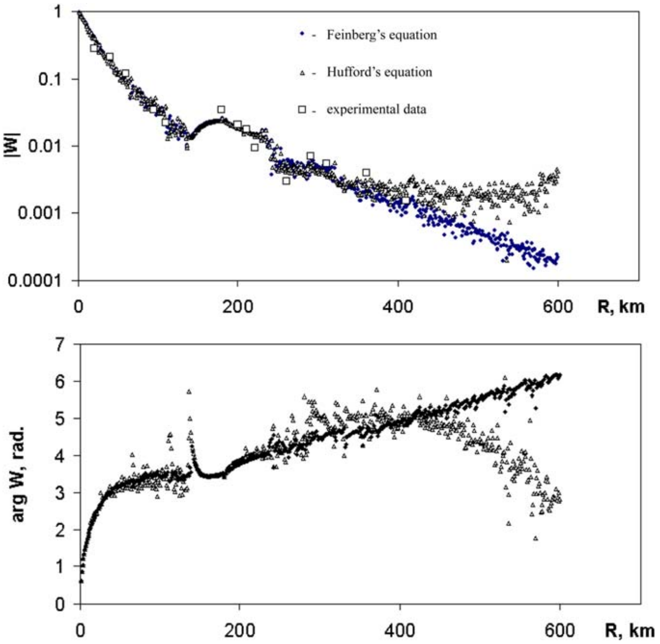

Fig. 3. A comparison of theoretical data of the module of the attenuation function $|W|$ carried out by two methods with experimental data.

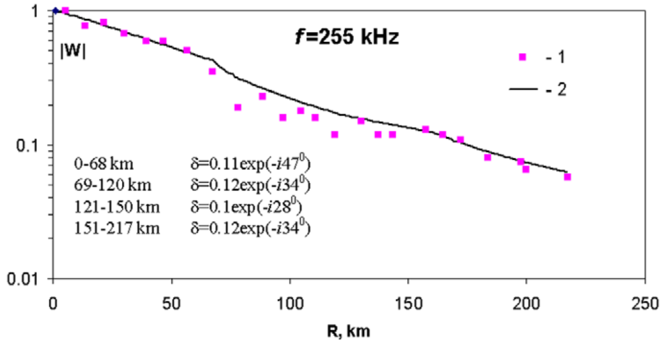

Fig. 4. Measured (1) and calculated (2) values of $|W|$ for the Choolman–Aldan radio path.

by means of Feinberg's integral equation are more stable on a large distance. Fig. 4 shows a comparison of measured (indicated by 1) and calculated (indicated by 2) values of the module of the attenuation function carried out by the same method at a frequency of 255 kHz. The radio path is permafrost Choolman–Aldan path that has four impedance sections.

Also we offered the algorithm and program of calculation of an attenuation function for multi-sectional impedance paths under the Kalinin–Feinberg's formula (up to six impedance sections) (Dembelov and Bashkuev, 2003). For three-sectional paths with electrical properties of q_1, q_2, q_3 the Kalinin–Feinberg's formula looks as follows (Feinberg, 1959):

$$W(\theta_0) = \sqrt{\mathrm{i}\pi M\theta_0}[q_1 - q_2][q_2 - q_3] \sum_{k,l,m=1}^{\infty} \frac{\exp\{\mathrm{i}M[\theta_1 t_k(q_1) + \theta_2 t_l(q_2) + \theta_3 t_m(q_3)]\}}{[t_k(q_1) - q_1^2][t_l(q_2) - q_2^2][t_m(q_3) - q_3^2][t_k(q_1) - t_l(q_2)][t_l(q_2) - t_m(q_3)]}.$$

The formula is alternative to the Feinberg's equation (1). Here $\theta_0 = \theta_1 + \theta_2 + \theta_3$ are angular distances, and $M = \sqrt[3]{\frac{ka}{2}}$ is Fock's parameter. The presented numerical expression for the attenuation function under the formula of Kalinin–Feinberg for multi-sectional paths allows us to have a stable solution for lengthy and low conducting paths at any frequencies of VLF–HF ranges.

Unknown laws of seasonal variations of an electrical condition status of the cryolitozone are revealed in the conditions of a rough continental climate and cryolitozone in the northeast part of Eurasia. We have developed the model of seasonal modulation phenomena both in an electromagnetic field and in GES parameters. Seasonal variations of impedance of a boundary surface lead to significant variations of LF–MF electromagnetic fields. During winter season the field grows quickly enough by 1.5–2.5 times in comparison with summer time. These strong seasonal variations of a field are attributed to both the seasonal changes of GES parameters in the top 10–25 m of the ground and physical properties of wood vegetation. It is proposed to create a cover map of electrical–physical parameters of various types of the wood environment.

6. Conclusions

Scientific results obtained are summarized as follows:

(1) Existence of frequency dispersion of ER of permafrost rocks is experimentally proved, and frequency dispersion of ER of frozen rocks arises from the multiphase nature of the frozen medium.
(2) Complex research of electrical properties of the Earth's the cryosphere is carried out, and significant volume of information on the geoelectric section of cryolitozone is obtained and systematized.
(3) Quantitative characteristics of surface impedance of various types of permafrost rocks necessary for the calculations of excitation and propagation of seismogenic electromagnetic emissions in the Earth cryosphere are obtained.
(4) The technique of geoelectrical mapping of the cryolitozone is proposed on the basis of radioimpedance measurements.
(5) A prediction map of geoelectrical sections of Northeast of Eurasia is generated.

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