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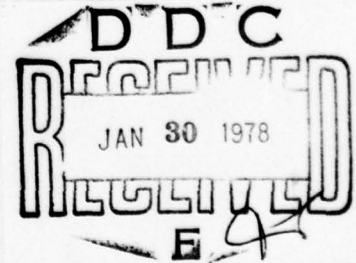DDC

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FOREIGN TECHNOLOGY DIVISION

SURVEY OF WORKS CONNECTED WITH UNDERGROUND
RADIOWAVE PROPAGATION

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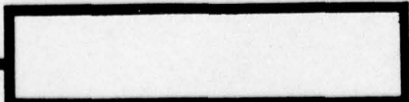
G. I. Makarov, V. A. Pavlov

UNEDITED MACHINE TRANSLATION

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SURVEY OF WORKS CONNECTED WITH UNDERGROUND RADIO-WAVE PROPAGATION.

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	A α ɑ	Nu	N ν
Beta	B β	Xi	Ξ ξ
Gamma	Γ γ	Omicron	O o
Delta	Δ δ	Pi	Π π
Epsilon	E ε ϵ	Rho	P ρ ϱ
Zeta	Z ζ	Sigma	Σ σ ς
Eta	H η	Tau	T τ
Theta	Θ θ ϑ	Upsilon	Υ υ
Iota	I ι	Phi	Φ φ φ
Kappa	K ϰ κ ϰ	Chi	X χ
Lambda	Λ λ	Psi	Ψ ψ
Mu	M μ	Omega	Ω ω

i

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

———

rot	curl
lg	log

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SURVEY OF WORKS CONNECTED WITH UNDERGROUND RADIOWAVE PROPAGATION.

G. I. Makarov, V. A. Pavlov.

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There are several reasons, which caused interest in investigations in the region of radiowave propagation in the earth's crust. for the first time such investigations they became to be occupied in connection with the needs of exploration geophysics. Subsequently to problem about the propagation of electromagnetic energy in the earth's crust was drawn the attention in connection with the solution of certain problems of electrodynamics and the technicians of the detection of electrical signals in the earth/ground. Finally, one of the last/latter motives is the need for the selection of the routes of radio communication, reliably shielded from interferences (propagation of the electromagnetic energy through the deep weakly conductive layers, covered with the high-conductivity rock/species).

The present article is the survey part of V. A. Pavlov's dissertation work, made under G. I. makarov's management/manual. By

the authors is made survey/coverage of the fundamental factors, which affect radio communication with the aid of the submerged into the earth/ground antennas: geological structure, type and the locations of the transmitting and receptors, the curvatures of the earth's surface, dependence of the electrical parameters of rocks on frequency, temperature and pressure, the radio jammings, etc. In the article are examined also the fundamental theoretical and experimental work on radiowave propagation in thicker than the Earth.

Given below information are borrowed from the literature sources, main from which they are [150, 146, 141, 138, 139, 142, 121, 21, 14, 96, 59, 60, 9-12, 110, 152].

§1. Structure of earth as a whole.

For the solution to the questions, placed in given work, primary meaning has the information about the electrical properties of earth as a whole, and auxiliary - data on the mechanical, thermal and other parameters of rock/species. Examination let us begin from survey/coverage of the representations of the division of earth into zones.

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Data on the mechanical structure of earth, as a rule, were obtained with the aid of seismic and gravimetric measurements [38, 40, 146, 14, 21]. The fundamental parts of terrestial globe they consider three of geospheres: crust, mantles (shell) and nucleus. The depth of the occurrence of the boundaries of the enumerated zones depends on the location of observation point on the earth's surface and from as are determined the very concepts of "crust", "mantle", "nucleus". The most universally recognized diagrams of the subdivision of earth to geospheres are the models of Bullen [14] and of Gutenberg [21].

As lower boundary terrestrial crust usually accepts the Moho surface [1].

FOOTNOTE [1]. Some authors determine in another way concept "lower boundary of crust", see, for example, [78]. ENDFOOTNOTE.

On it proceeds a velocity jump of the longitudinal seismic waves V_p from 6.7 to 8 km/s. Will lie this surface on the average at depth 33-35 km [20, 13, 31]. On continents it, as a rule, is arranged

deeper (to 60-70 km), and near the oceans it lie/rests at several kilometers under the bottom. There are at present several hypotheses about the nature of the formation of Moho surface [93, 107, 117, 90, 41, 19, 51, 52, 57]. two opposite points of view are expressed in works [90, 107] and [93, 117].

Under Moho surface stretches the mantle (shell of earth). As its lower boundary is accepted the sphere of a radius 3473 km, on which proceeds the second sharp velocity discontinuity V_p the longitudinal seismic waves from 13.6 to 8.1-10.4 km/s [14]. Within this sphere is arranged the nucleus of earth. Crust, the mantle and the nucleus in themselves are heterogeneous; therefore them they subdivide into smaller geospheres.

They distinguish of two fundamental types of the earth's crust: continental and oceanic [2].

FOOTNOTE [2]. There is a more detailed subdivision of crust to subtypes [31, 34, 35, 43]. ENDFOOTNOTE.

Continental crust [62] is composed of the soil deposit of the most diverse composition, sedimentary rocks (their density 2.6 g/cm³, $V_p < 4.5$

km/s), of granite array (density 2.7 g/cm^3) and of "basaltic" layer (density 2.9 g/cm^3, $V_p = 6,3-7$ km/s). Last/latter name conditionally [62, 41]. Due to a deep occurrence the composition of this layer is not accurately known. It can be judged only from indirect data. In any case the velocity of the longitudinal waves in this layer sufficiently considerably differs from the velocity in strictly basalt (for which $V_p = 5,0-6,0$ km/s), and this indicates that it, besides basalts, includes other rock/species. During transition from continental crust to oceanic disappears soil deposit and decreases the thickness of granite layer. Oceanic crust consists of precipitation and "basaltic" arrays. The boundary between granites and "basalts" is called Conrad's surface.

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The reasons for the sharp difference in the structure of oceanic and continental crust insufficiently are well studied [by 41, 13].

In turn, the mantle (shell of earth) according to seismometric properties is divided by three zones [21, 62, 14]:

(1) Зоны	V_p, км/сек (2)	(3) Плотность, г/см³ (4)
B	7,8 — 9,0	3,64 — 4,07
C	9,0 — 11,4	4,68 — 4,41
D	11,4 — 13,6	5,69 — 5,57*

Key: (1). Zones. (2). km/s. (3). Density. (4). g/cm³.

FOOTNOTE. At depth 2900 km. ENDFOOTNOTE.

The nucleus of earth also is divided by three zones:

(1) Зоны	V_p, км/сек (2)	(3) Плотность, г/см³ (4)
E	8,1 — 10,4	11,5 — 12,0
F	10,4 — 9,5	15
G	11,2 — 11,3	17,3 — 17,9

Key: (1). Zones. (2). km/s. (3). Density. (4). g/cm³.

The nature of the mechanical foliation of earth insufficiently is well studied [by 31, 34, 41, 52, 57]. Is explained this by great difficulties in obtaining the experimental data, since many of them they are indirect, and therefore the interpretation of such data often leads to many-valued answer/response.

Watt and others [146] on the basis of the generalization of results [21, 38, 83, 89, 115] constructed averaged curves of the dependences of temperature and pressure on depth. For the first eight of kilometers they are based on direct measurements in Wales, while for large depths - on the extrapolation of the results of the measurements, obtained near from surface. These curve/graphs are given in Fig. 1A and b. On the first eight kilometers of depth there is a considerable scatter of values of the gradient of temperature. The average temperature gradient in sedimentary rocks is approximately 30°C/cm, and maximally observed - approximately 70°C/cm.

Let us now move on to the examination of the structure of earth from the viewpoint of its electrical properties.

The contemporary magnetotelluric and geomagnetic investigations, given of the laboratory analyses of the samples of rocks, and also the information about radiowave propagation through the thickness of terrestrial rocks show [110, 121, 141, 146, 150] that according to electrical properties the Earth as a whole has laminar structure. The earth's crust on the dependence of the electrical parameters on depth roughly can be subdivided into three classes: 1) continental crust; 2) oceanic, 3) transient from the continental to oceanic. The deeper layers of earth (lower part of the mantle and nucleus), apparently, have similar on entire terrestial globe electrical structure.

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Let us pause at the first two classes of the earth's crust. Both have a minimum of electrical conductivity, but they differ in terms of its numerical value and the depth of occurrence [121, 146, 152]. The weakly conductive layer will lie on the depth of several kilometers under the ocean floor. much more deeply it is arranged under continents (dozen kilometers) and still deeper - in mountain areas. About 5o/o of space of the earth's crust compose [152] sedimentary rocks (sandstone, limestone, schists). They possess in essence [30, 53, 146] high ($10^{-3}-10^{-1}$ 1/ohm•m) electrical conductivity they will lie on depth several kilometers under continents. Near the oceans the upper precipitation layer has

thickness in hundreds of meters and its electrical conductivity it
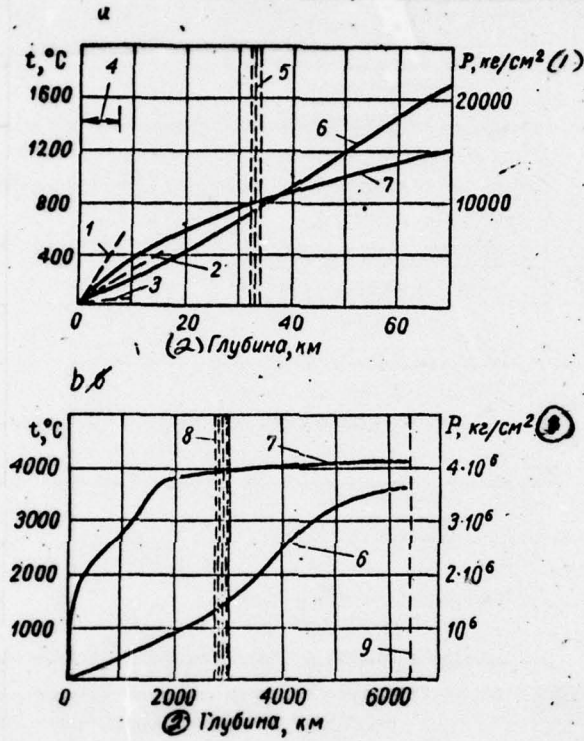reaches unity (1/ohm•m) [121, 150].

Fig. 1.

Fig. 1. the averaged graph/diagrams of the dependence of temperature t and of pressure P within earth on submersion depth from 0 to 70 km (a) and from 0 to 6370 (b). 1 - upper boundary of change t with depth; 2 - the average slope of the graph/diagram of dependence of t on depth; 3 - lower boundary of change t with depth; 4 - direct observations (Wales); 5 - Mohorovicic's boundary; 6 - pressure; 7 - temperature; 8 - the boundary of nucleus; 9 - the center of earth.

Key: (1). kg/cm². (2). Depth, km.

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95o/o of space of the earth's crust occupy volcanic rock (granites, basalts, labradorites, granodiorite, rhyolite, gabbro). Typical for them is low $(10^{-8}-10^{-11}$ 1/ohm•m) electrical conductivity. thickness of the layer, formed by volcanic rock on continents, reaches to 50 km, and near the oceans - to 10 km [152]. It is interesting to note that the minimum of electrical conductivity usually falls on the layer, named higher "basaltic". Continental "basaltic" layer was formed during other conditions, than oceanic. It is located in the region of large pressures and temperatures and because of this has high electrical conductivity. On the basis laboratory findings (see §2) of volcanic rock it is possible to assume that electrical

conductivity in this layer is tentatively equal to $10^{-5}-10^{-7}$ 1/ohm•m, i.e., approximately by four orders is higher than in oceanic "basalt".

Electrical conductivity of rocks depends [110] on concentration and mobility of charge carriers. Depending on conditions (temperature, pressure, the character of heterogeneities) charge carriers can be the electrons, ions in ore, ions in solutions, or the combination of these carriers [146]. At depths of up to the hundreds of meters electrical conductivity of rock/species is determined mainly by ions in the solutions, filling the pore. During insertion the pressure and the temperature increase. A pressure increase causes a reduction of the space of pores, but temperature rise increases the dissociation of salts and ion concentration in solutions and to a lesser degree - ion mobility. At depths about kilometer on continents the effect of natural water on electrical conductivity strongly decreases and by only charge carriers they stop the electrons and the ions of solid. It proves to be (see §2) that the effect of pressure cn electrical conductivity becomes negligible in comparison with temperature.

In the lower part of the earth's crust because of an increase in the temperature (see §2) occurs an increase in electrical conductivity [146], and on the boundary of lower mantle with nucleus

it reaches (according to data on slow variations in the magnetic
field of earth) value of 10^2-10^3 1/ohm•m [135]. Apparently, nucleus
itself consists of metallic substance, which is located at
temperature of $4•10^3$°K and pressure $1.35•10^6-4•10^6$ kg/cm² [38].
Electrical conductivity of nucleus by order of value must coincide
with electrical conductivity of metals under these conditions.

Unlike electrical conductivity, which is changed in depth on
several orders, dielectric constant changes approximately by an order
(from dozens unity CGSE on surface to unity CGSE in the depths of
volcanic rock) [17, 110, 129, 130, 150].

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However, this clear the strongly moistened, porous rocks. In them
dielectric constant reaches 10^3-10^4 unity CGSE at low frequencies
[104, 129, 130], it increasing with an increase in the humidity and
decreases with an increase in the frequency.

In recent years are made the attempts at the ultradeep drilling
of the earth's crust, also, on continents, and near ocean [44]. Are
realized two grandiose projects ("Mohole" and the "upper mantle"),
the directed toward comprehensive study deep layers of crust and
upper part of the mantle of earth. The realization of these projects

the electrical parameters of different rock/species over a wide range of pressures and temperatures [17, 30, 49, 48, 75, 53, 146, 110].

the measurements showed [17, 49] that of all investigated by the authors specimen/samples electrical conductivity and dielectric constant increased with a pressure increase (Fig. 2 and 3). But all the same there are [48] and such rock/species (augitic porphyrite, serpentinous dunite, pyroxenite), which have the anomalous dependence of electrical conductivity on pressure. Dielectric constant under the effect of pressure to $5 \cdot 10^3$ kg/cm^2 (which corresponds to depth 20 km) increases only several times [17]. A further increase in the pressure virtually does not change dielectric constant. For pure/clean minerals and dense dry rock/species the electrical conductivity is subordinated [53] to the law

$$\sigma = \sigma_0 e^{-E/kT}, \tag{1}$$

where E - energy of activation, k - the constant of Boltzmann, T - temperature, °K.

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will give the more detailed and more reliable information about the internal structure of earth.

§2. Laboratory investigations of the dependence of the electrical parameters of rocks on temperature and pressure.

The existing at present methods of the measurement of the electrical parameters of rock/species under field conditions do not make it possible to measure the electrical conductivity of the deep weakly conductive layers. Measurements in this region are hinder/hampered by the shielding effect of surface rocks. The interpretation of the results of measurement stops not by always single-valued as a result of the complexity of geological structure crust and the mantle of earth. To aid come the methods, which make it possible to construct the variation of the electrical parameters on depth. They are based on the laboratory investigations of specimen/samples with the enlistment of some supplementary information: the course of temperature and pressure with depth (see Fig. 1A and b) and the character of the distribution of rock/species according to depth (it can be judged, for example, from data of drilling and the results of gravimetric and seismic observations). In the Soviet Union and abroad were carried out the investigations of
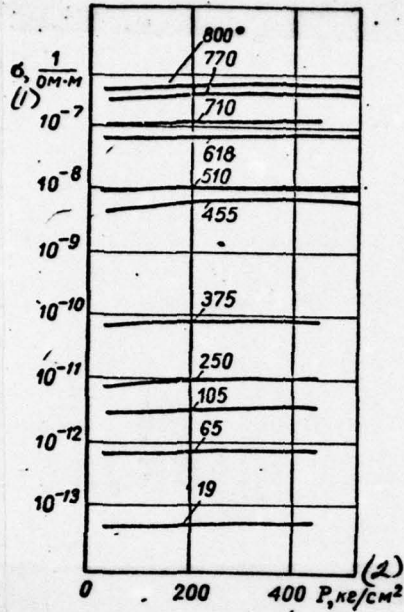
Fig. 2. Dependence of electrical conductivity of diabase σ on pressure at various temperatures, according to data [49].

Key: (1). Ω·m. (2). kg/cm².

Fig. 3. Dependence of the ratio of dielectric constant   (at pressure P) to dielectric constant   (with atmospheric pressure) on pressure, according to data [17]. 1 - limestone; 2 - granite; 3 - basalt; 4 - diabase.

Key: (1). kgf/cm².

Fig. 4. Dependence of electrical conductivity σ 1/ohm•m basalt on temperatures at different pressures.

Key: (1). Ω•m. (2). kg/cm².

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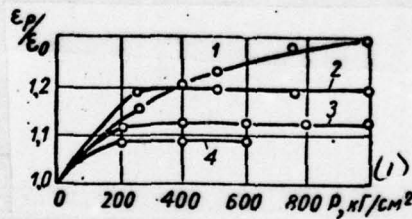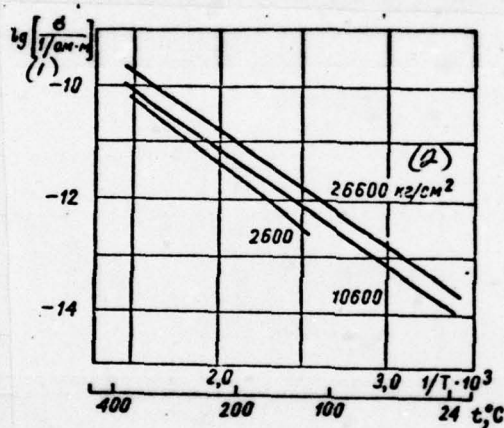With an increase in the temperature of humid porous rock of complex mineral composition occur the changes in its phases, which can influence electrical conductivity of rock/species. Therefore experimental dependence σ (T) can differ from law (1). Figure 4 gives the experimental dependence of electrical conductivity of basalt on temperature, constructed on the basis of data [48]. Since specimen/samples were dry and dense, curve/graphs were subordinated to equation (1). Under the simultaneous influence of pressure and temperature [17] on diabases, basalts, peridotites and sandstones their electrical conductivity depended on pressure much weaker than on temperature. This conclusion was confirmed and by subsequent experiments [48], during which the pressure rose to $4 \cdot 10^4$ kg/cm² (which corresponds to depth 150 km), as a result of which occurred a change in the electrical conductivity in all to 70o/o. An increase in the temperature only to 800°C (depth 34 km) produces an increase in the electrical conductivity by 5-6 orders. In work [105] is investigated the electrical conductivity of peridotite at pressures to 10^4 kg/cm² and temperatures to 1200°C. It grew/rose with an increase in the temperature and decreased under the effect of pressure on 2.3-3.7o/o on each of 10^3 kg/cm².

Work [1] gives given data on research on electrical conductivity of single crystals NaCl during shock compression in the range of pressures from $5 \cdot 10^4$ to $8 \cdot 10^5$ kg/cm². In the upper pressure range th

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temperature of these single crystals T rose to 6150°K (i.e. it exceeded the temperature in the center of the nucleus of earth), and electrical conductivity σ it reached value $3.3 \cdot 10^{-2}$ 1/ohm·m. It is interesting that the graph/diagram of dependence lg σ (1/T) in high-temperature range had the constant slope/inclination, corresponding to energy of activation 1.2 eV. This means that a fundamental effect on electrical conductivity has the temperature, whereupon it as under standard conditions, introduce ionic character. The weak (in comparison with temperature) effect of pressure on electrical conductivity note other authors [110, 123].

Utilizing a known variation of temperature with depth (see Fig. 1A, b, some authors [110, 121, 146, 150] they constructed the dependence of electrical conductivity as function of the depth of immersion. In Fig. 5 we have constructed the dependence σ on submersion depth according to data of these authors. For the upper layers of crust the construction was made on the basis of the results of field investigations with the enlistment of these laboratory measurements of the parameters of sedimentary rocks during an increase in temperature and pressure. In Fig. 5 branches AB and $A_1 B_1$ are the tentative upper and lower boundaries of electrical conductivity of sedimentary rocks on continents.

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The branch $B_1C_1D_1$ characterizes lower boundary of electrical conductivity near oceans [121, 150]. For the lower layers of crust the dependence of electrical conductivity on pressure can be disregarded and allowed the only effect of temperature. So were constructed [146] branches BE and D_1E_1. Electrical conductivity of the upper mantle (branch EF and E_1F_1) was found [by 146] according to data of geomagnetic sounding. It proves to be that the graph/diagrams of the dependence of electrical conductivity on the depth, obtained by the authors [110, 150], are arrange/located between branches ABEF and $A_1B_1C_1D_1E_1F_1$. The curves MN and M_1N characterize upper and lower boundaries of electrical conductivity of sea water.

According to data [17, 30, 59, 60, 104, 110, 129, 146, 150, 152] in Fig. 6 are constructed the exemplary/approximate upper and lower boundary of the measurement of dielectric constant with depth (branches ABC and $A_1B_1C_1$). The constructions were made on the basis of the laboratory measurements of dielectric constant at the different values of temperature, pressure and field frequency. Branch BC is based on the temperature dependence of volcanic rock at frequency 1 kHz, into branch B_1C_1 - on analogous dependence at frequency 100 kHz.
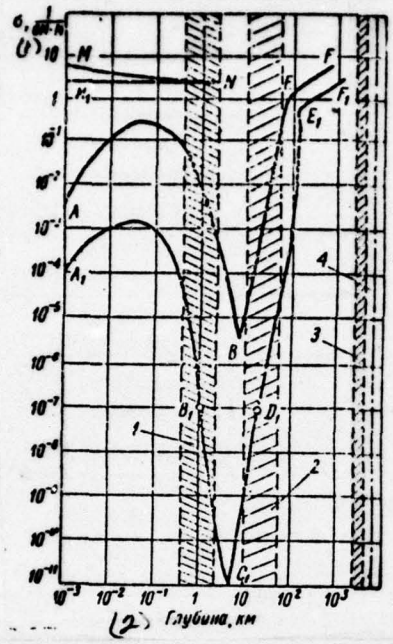
Fig. 5. Tentative upper (ABEF) and lower ($A_1B_1C_1D_1E_1F_1$) boundary of the dependence of electrical conductivity of earth on depth and upper

(Mn) and lower (M_1N) boundary of the dependence of electrical conductivity of sea water on submersion depth. 1 - the boundary of Conrad; 2 - Moho boundary; 3 - the boundary between the nucleus and the mantle; 4 - the center of earth.

Key: (1). $\Omega \cdot m$. (2). Depth, km.

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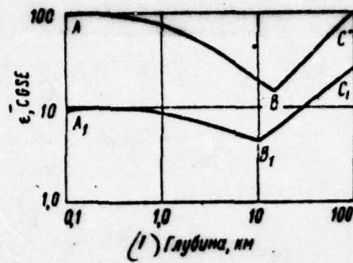
Fig. 6. Tentative upper (ABC) and lower ($A_1B_1C_1$) boundary of the dependence of the dielectric constant of earth ϵ on submersion depth.

Key: (1). Depth, km.

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With depths less than 100 m is probably feasible the larger scatter of the values of dielectric constant as a result of the considerable diversity of the being encountered rock/species, different porosity, humidity, and also due to the presence of dispersion.

In conclusion must be noted that the representation of the electrical properties of the earth is based on the limited observations. They not always make it possible sufficiently to

accurately and unambiguously determine the electrical parameters of rock/species. Therefore the results of the subsequent investigations, apparently, can influence these representations.

§3. Dependence of the electrical parameters of rock/species on frequency.

One of the essential problems, connected with underground radiowave propagation, is the investigation of the character of the dependence of the electrical parameters of rock/species on frequency. During the solution of this problem we encounter with great theoretical and experimental difficulties. During laboratory measurements, for example, is necessary the account of transient capacitance/capacities, effects of polarization, contacts metal - specimen/sample, the finite dimensions of specimen/samples and change in their structure in comparison with that, which they had in natural conditions, etc. During measurements under trifling conditions it is necessary to consider discontinuity in depth and in horizontal direction (heterogeneity has a different effect on electrical and magnetic fields [73]). Obtaining these information by itself represents sufficiently difficult problem. All this led to the fact that at present there is no unified opinion about the dispersion of

the electrical parameters of rock/species. Detailed survey/coverage
of the work, dedicated to investigations in this region, is conducted
by A. G. Tarkhov [59, 60]. Author himself notes that his conclusions
did not obtain universal acclaim. In his opinion, contemporary
geophysical investigations make it possible to consider that up to
frequencies, equal at least 3-10 MHz, the electrical parameters of
homogeneous rocks can be considered not depending on field frequency.
But position is changed, when it is necessary to examine complex
rocks (for example, the ore phenocrysts), in which along with
conduction currents are bias currents. The role of the latter
increases with an increase in the field frequency. It is necessary to
note that the greatest disagreements concern the dispersion of the
electrical parameters of surface, moistened and porous rocks
[155-157].

In work [27] are investigated the specimen/samples, extracted
from depth 2 m, in the range of frequencies from 0 to 200 kHz. For
measurements was applied electrothermal method. This made it possible
to get rid of bias currents and to observe the effect of conduction
currents. At higher frequency the electrical conductivity of sand
increased 1.8 times, and clay - 1.2 times. For the checking of
results were carried out the measurements by other methods.

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Is examined [by 129] the effect of different humidity on the dispersion of the electrical parameters of the specimen/samples of surface rock/species. It turned out that at frequency 1.2 kHz electrical conductivity of specimen/samples with the natural moisture content 15o/o 10 times is more electrical conductivity of dried specimen/samples. The author changed frequency in range from 100 kHz to 10 MHz. With humidity 3.6o/o electrical conductivity during an increase in the frequency grow/rose 15 times. Was measured also [29] the dependence of the dielectric constant of humid and dry rock/species on field frequency in the range 100 kHz - 20 MHz. In order to eliminate the effect of direct contact the metal, rock/species,, was made air gap between the plates of capacitor and the specimen/sample. For a gap capacitance is derived the formula, which makes it possible to consider its effect. Dielectric constant at higher frequency was 3-14 times less than its value at lower frequency. Dispersion to larger degree depended on the humidity of specimen/samples, than on the character of rock/species themselves (so, with an increase in the humidity dispersion it grow/rose).

In the wide interval of frequencies (50 Hz - 30 MHz) is measured [by 104] the dispersion of the dielectric constant of the large number of rock/species (both precipitation and volcanic). In the

range 10 - 30 MHz it decreased less than 2 times. in the range from
50 Hz to 10 kHz with humidity 12o/o dielectric constant at lower
frequencies reached $4 \cdot 10^4$ CGSE, and a decrease in the humidity to
2o/o caused a decrease in the dielectric constant to 40 CGSE. R. L.
Smith-Rose [129] at field frequency 500 Hz obtained the value of
dielectric constant, equal to 10^4 CGSE.

On the department of radiophysics of L.G.U. were carried out the
studies of the dispersion of the electrical parameters of surface
rocks of different humidity and structure during a change in the
field frequency from 400 kHz to 30 MHz. Considerable attention was
allotted to research on the effect of the mobility of the aqueous
solutions of salts in the pores of rock/species on dielectric
constant in lower frequency band. For example, specimen/sample made
of clay lumpy rock/species at field frequency 400 kHz had dielectric
constant 220 CGSE and electrical conductivity of order $3 \cdot 10^{-7}$
1/ohm•m.

The dispersion of the electrical parameters of volcanic rock was
studied [by 110] in the range of frequencies from 100 Hz to 500 kHz
with temperatures from 200 to 1050°C (Fig. 7 and 8). These
temperatures correspond to depths from 5 to 50 km. At depths more
than 40 km the electrical parameters of rock/species in practice do
not depend on field frequency. At depths on the order of 5 km of a

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change in the frequency from 200 Hz to 40 kHz it produced an increase
in the electrical conductivity 40-50 times. The dependence of
dielectric constant on frequency for volcanic rock was expressed much
weaker.

On the basis of the considerations, given in this and the
preceding/previous paragraphs, it is possible to draw the conclusion
that during the investigation of radiowave propagation through the
"basaltic" waveguide it is possible to disregard the dispersion of
the electrical parameters in comparison with effect by such factors
as, for example, the heterogeneity of crust in depth. To the
propagation of the radio-will through sedimentary rocks (especially
through rock/species with the increased humidity) the dispersion can
have a noticeable effect.

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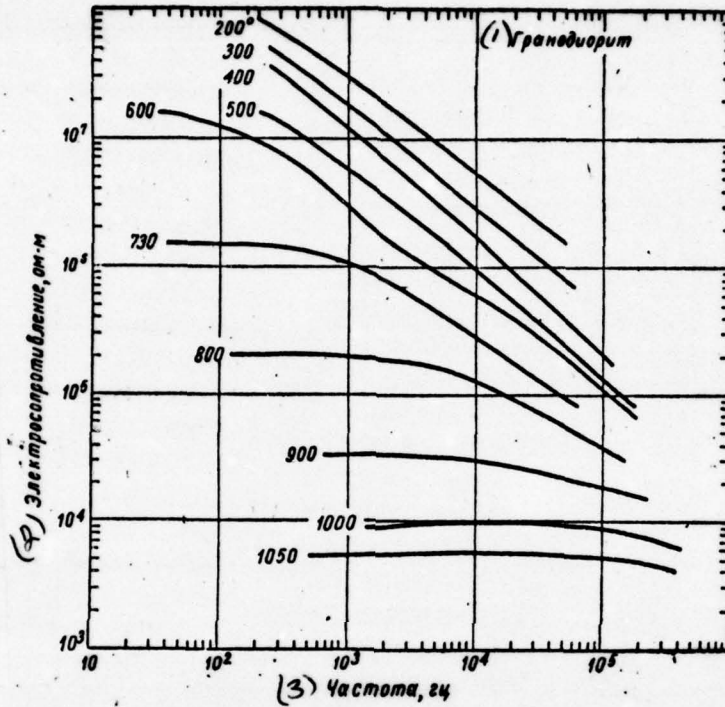
Fig. 7. Dependence of the electrical resistance of granodiorite on frequency at various temperatures (into °C).

Key: (1). Granodiorite. (2). Electrical resistance, Ω•m. (3). Frequency, Hz.

28
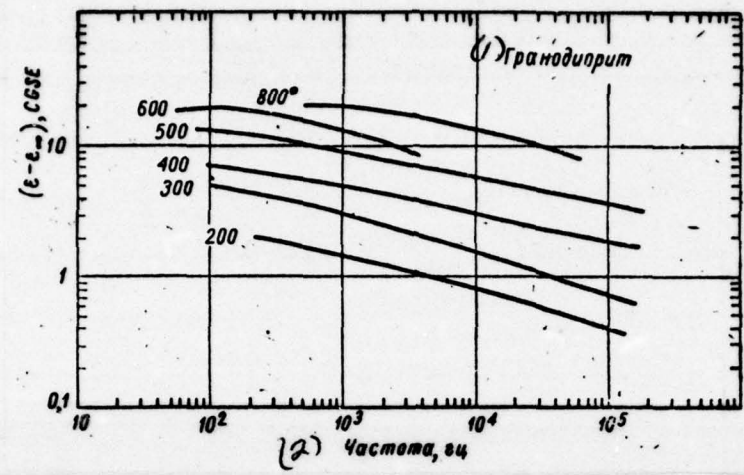
Fig. 8. Dependence of the dielectric constant of granodiorite on frequency at different temperatures (into °C). '. — 7.10 —: value ' with the tendency of frequency toward —; : does not depend on temperature.

Key: (1). Granodiorite. (2). Frequency, Hz.

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§4. Theoretical studies of underground radiowave propagation.

Investigations in this region depending on the model of earth in question it is possible to break into two groups.

1. Solution of the problem of underground source under the assumption of the flat/plane uniform model of earth. This problem actually is the small modification of Sommerfield's classical problem [26], [131]. A difference of it from the latter is in the fact that the source is arranged in medium with losses, optically denser, than external half-space (air). In this case appear some specific mathematical difficulties, absent in Sommerfield's classical problem. The most complete analysis of this problem is given in works [9-12, 66, 138, 139].

It is necessary to note that the flat/plane uniform model of earth is the sufficiently rough idealization of actual conditions. It is justified when the heterogeneity of the electrical properties of earth does not introduce large changes into the character of

radiowave propagation. This is possible, apparently, during the shallow insertion of the antennas, when the mechanism of propagation in essence is determined by the so-called "lateral" waves. The precise limits of the applicability of flat/plane uniform model can be obtained, if we achieve the considerably more difficult purpose of radiowave propagation in the heterogeneous Earth.

2. Investigation of problem under the assumption of the heterogeneous model of earth. The solution of this problem is connected with great mathematical difficulties; therefore it is necessary to examine the concrete/specific/actual approximations of the electrical properties of earth. The advantage of this approach is the possibility of the account of the effect of the weakly conductive "basaltic" layer on the mechanism of radiowave propagation. It proves to be that under some conditions the "basaltic" layer can play the role of waveguide for channeling of electromagnetic energy.

There are several survey/coverages [55, 100, 134, 142, 154], which concern the different sides of the problem of underground radiowave propagation. Their presence makes it possible to stop at the examination only of most essential investigations. Let us examine first the works, which relate to the first group of experiments.

L. M. Brekhovskikh [9-12] solved the problem of radiowave

propagation from the vertical electric dipole, placed into
homogeneous medium with losses (earth/ground).

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To them is used the been at present classical method of the
resolution of spherical waves for the superposition of heterogeneous
(having composite direction cosines) plane waves. The effect of the
interface of mediums manifests itself the appearance of the secondary
field in the earth/ground, expression for which is constructed in the
form of contour integral. Specific for a problem of underground
source is that the initial integral for the secondary field can be
broken into integral in terms of the duct of crossing and integral in
terms of the shores of cut/section. In the approach/approximation of
geometric optics each integral it is possible to ascribe clear
physical sense. Computation of the first integral gives the wave,
reflected from boundary. L. M. Brekhovskikh examined only the case of
a sufficient distance of the pole of integrand of saddle point, which
corresponds to large numerical distances on the earth/ground [1].

FOOTNOTE [1]. numerical distance on the earth/ground is named
dimensionless quantity $ik_1 r/2 [(k_0/k_1)^2 + 1]$, while by numerical
distance by air - value $ik_0 r/2 [(k_1/k_0)^2 + 1]$, where k_0 is wave

number in air; k_1 - wave number in the earth/ground; r is a distance between correspondents. ENDFOOTNOTE.

Reflecting concept turns out to be that which is used only during the removal of transmitter and receiver from interface. Integral in terms of the shores of cut/section gives the so-called side wave. It makes sense of wave, leaving from source to the interface of mediums at an angle of total internal reflection. This waves is refracted on boundary, lands in air, further it is propagated along interface and then returns to the earth/ground. A deficiency/lack [9-12] is the fact that the expression for a side wave, obtained L. M. Brekhovskikh, is applicable only at large numerical distances by air. This is the consequence of the fact that was not taken into account close location of one of the poles and the branch point.

More common/general/total result is obtained by Ye. L. Feynberg [66]. It found expression for a side wave with the use of a concept of the function of weakening (which is equivalent to the application/use of the modified steepest descent method [68] taking into account the close location of pole and saddle point). The expressions for a side wave at large numerical distances from air, obtained L. M. Brekhovskikh and Ye. L. Feynberg, coincide. In this region the field decreases inversely proportional to the square of

the distance between the correspondents. At small distances it
decreases inversely proportional to the first degree of distance.
Typical for an underground radiowave propagation is that horizontal
the component of electric field approximately $|\sqrt{\epsilon'_m}|$ times is more
vertical (ϵ'_m — is a relative composite dielectric constant).

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It is interesting to note that in communication/connection with the
aid of buried antennas on side wave there is a optimum (in the sense
of producing the maximum field at the point of method) frequency.
Generally speaking, it depends on the total insertion of antennas,
the electrical properties of earth and distance between antennas, but
if numerical distances by air either are very small or very great on
comparison with unity, then the optimum frequency it does not depend
on the distance between the correspondents. The results of
investigations [9-12] and [66] are used when $|k_1 r| \gg 1$.

The horizontal electrical antennas are the more effective
underground sources of radio waves, than vertical. The radial
component of electric field, created by horizontal antenna, $|\sqrt{\epsilon'_m}\cos\varphi|$
times is more than the same component, created by vertical wire
antenna under the condition of the equality of their dipole moments [1]
(φ is an azimuth angle).

of space. The dependence of electrical conductivity σ on depth z for it has the form

$$\sigma(z) = \begin{cases} 0 & \text{with} \quad -\infty < z < -h \cdot \quad \text{(air)} \\ \sigma_g = \text{const} & \text{with} \quad -h < z < 0 \quad \text{(screen)}, \\ 2\varepsilon_0 K_0 \omega e^{\beta(z-z_0)} & \text{with} \quad 0 < z < z_0 \quad \text{(waveguide)} \\ \infty & \text{with} \quad z \geqslant z_0 \quad \text{(foundation of waveguide)}, \end{cases} \quad (2)$$

where K_0 and β are selected from the condition of the coincidence of the approximating and experimental dependence σ (z). Dielectric constant is taken different, but by constant in each layer. This approximation of the properties of medium makes it possible to express the solution of the problem by cylindrical functions.

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As the Wait source it examined the vertical electric dipole, placed into waveguide. A vital difference of the work of Wait from [9-12, 66, 139] is that contour integral for a potential it calculates

FOOTNOTE [1]. This is correct in that region, where the field of straight line and reflected waves is negligibly weak in comparison with the field of side wave. ENDFOOTNOTE.

Radio-wave emissions from underground electrical horizontal antenna in the case of the flat/plane uniform model of earth it is investigated by Д. R. Ueyt [139] and by Ye. A. Feynberg [66]. We found expression for the component of field at $|k_1r| \gg 1$ and any numerical distances by air.

Let us pass to the examination of the works, which relate to the second section. The geological structure of earth is such (see §1), that the insertion of the transmitting and receiving antennas to considerable depths leads to the possibility of the onset of the new mechanism of radiowave propagation. The weakly conductive "basaltic" layer begins to play the role of waveguide. In the earth's crust the electrical parameters of rock/species are the complex functions of depth. are possible the different approximations of these parameters. Д. R. Ueyt, examining the possibility of waveguide radiowave propagation to crust, accepts [141] the flat/plane four-layer model

according to deductions in the poles of integrand. This corresponds to field expansion in terms of modes (waveguide mechanism of the propagation of waves). The application/use of this method most is effective in remote zone from emitter. The fundamental difficulty is comprised in the solution to characteristic equation for the determination of poles. Wait solves by its method successive approximation. For this initially it makes the following assumptions:

1) the shielding layer is considered high-conductivity that it makes it possible to use approximations for the coefficients of reflection of separate modes from screen;

2) are assumed that the thickness of screen h much more the depth of the layer of skin effect (neglect of the mechanism of the side waves, which emerge into air);

3) are considered that surface z = 0. perfect dielectric; this assumption strongly simplifies the solution to characteristic equation.

As a result to analytically find zero approximation of solution, and then it is possible to find correction term. The attenuation of waves is characterized by exponential factor, whereupon index in exponent turns out to be that which was broken for the sum of three

terms, each of which it is possible to ascribe the physical sense. So, first term (A_n) describes the attenuation of modes because of the outflow of energy down $(z > 0)$, whereupon with an increase of the number of mode this attenuation increases. Second term (B) characterizes attenuation because of the final conductivity of screen, and the third (D) - because of losses in the medium of waveguide. The latter of two terms do not depend on the number of modes. By Wait were obtained numerical results for the first two modes and was examined the case, when $K_0 = 9$, $\beta \sim 1$ km^{-1}, $z_0 = 40$ km, $\lambda = 45$ km (wavelength in air): 1) with $\rho_g = 10^{-2}$ 1/ohm and $\sigma_0 = 10^{-8}$ 1/ohm it turned out that $A_1 = 2.8$, $A_2 = 28$, $B = 2.8$, $D = 5.4$ db/1000 km; 2) with $\sigma_g = 1$ 1/ohm and $\sigma_0 = 10^{-9}$ 1/ohm it turned out that $A_1 = 2.8$, $A_2 = 28$, $B = 0.28$, $D = 5.4$ db/1000 km. Are constructed the graph/diagrams of dependence A_1 and A_2 on β at the different values of ratio z_0/λ_0 (where $\lambda_0 = \lambda/\sqrt{K_0}$), see Fig. 9a and b. A deficiency/lack in the model of Wait [141] is the sufficiently rough approximation of the electrical properties of earth (conduct of sharp interfaces according to electrical properties within crust). By it is examined the only flat/plane model of earth, which limits the region of the applicability of the obtained results.

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By the authors of present article is investigated the more

general approximation of the electrical properties of earth.
Dependence of electrical conductivity and electrical properties of
earth. The dependence of electrical conductivity and dielectric
constant on depth is taken in the form of function of the type of
potential well. This it makes it possible to describe sufficiently
well the electrical properties of earth up to nucleus. As emitter is
examined horizontal electric dipole, and as the model of earth is
accepted sphere. The solution of problem succeeds in expressing by
Whittaker functions [18, 23, 33, 64, 88, 128]. The obtained results
will be published in one of the nearest issues of the present
collector.

In conclusion it is necessary to note that the analysis of
antenna systems in the earth/ground (as generally in mediums with
high electrical conductivity) differs significantly from their
analysis in air. occurs this due to the dissipation of
electromagnetic energy in near from emitter zone. useful information
on this question can be found in works [91, 120, 133, 134, 143, 147,
151].

§5. Experimental study of underground radiowave propagation.
Interference effect.

The publications, dedicated to this question, it is very small. Hansen [100] in regard to this writes that the majority of results "is buried" in the reports of the instituticns, which conducted similar research.
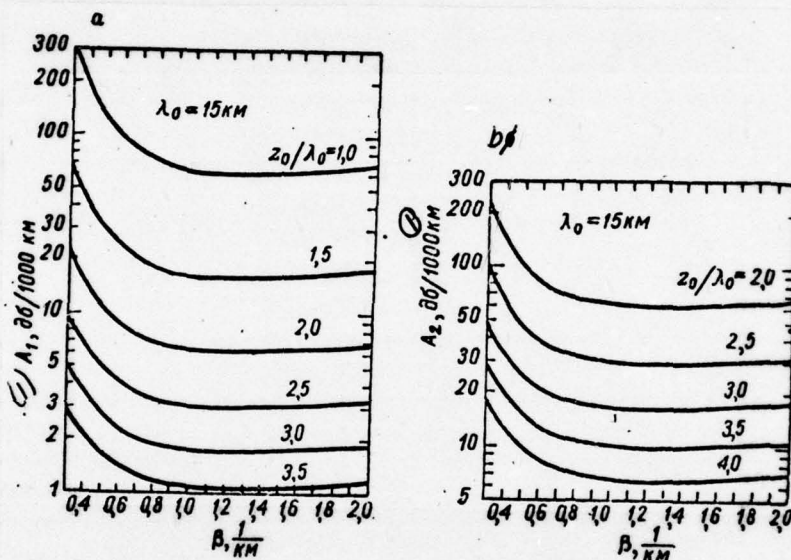

Fig. 9. Dependence of the coefficients of weakening λ_1 (a) and λ_2 (b) on the parameter β at the different values of ratio z_0/λ_0.

Key: (1). db/1000 km.

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Part [79, 113] has descriptive character, in the article [96] it is given very few the experimental data, and investigations [85, 102, 127] concern radiowave propagation in strongly-conducting mediums.

R. N. Ghose [96] experimentally investigated radiowave propagation from the horizontal antenna, placed into shaft/mine at depth 90 m. The receiver was driven out on 11 km and was arrange/located on the surface of the Earth. The author made comparisons of theoretical and experimental dependence the components of field E_x in the maximum of radiation pattern on frequency in the range 0.1-2.5 kHz (Fig. 10). The current moment in antenna $I_0 h_0$ was equal to 1.2 $\times$ 10⁶ a • m, and electrical conductivity of the Earth was 0∠157 1/ohm•m.

The experiment of radio communication with the aid of side wave at a distance 24 km (at the power of transmitter into 3 W) was described by G. A. Bernard [79]. transmitter with a power 30 W increased the range of communication/connection to 80 km. Articles [113, 153] describe the experiments of radio communication through

the weakly conductive layers. Was demonstrated [113] radio communication through the stone layer at frequency 200 kHz up to distance 29 km. The power of transmitter was 100 W. Noted, that there is an hope to increase range to 80-160 km, decreasing the frequency to 15-40 kHz. Was produced the transmission of the radio signals through the layer of rock salt and potash [153]. the transmitter and the receiver, spread up to distance 7 km, were placed in shafts at depth 300 m, but the power of transmitter was about 200 W. Communication/connection was realized at frequency 150 kHz by a teleprinter with a velocity of 60 words per minute. The experiment showed that the upper layer of the Earth was a good screen from interferences. [85, 102, 127] are dedicated to research on radiowave propagation from all possible antennas in the high-conductivity aqueous solutions. The advisability of such investigations seems us by very doubtful, since previously were known the electrical parameters of mediums.

Let us pass to the study of the problem concerning the effect of electromagnetic interferences on radio communication.
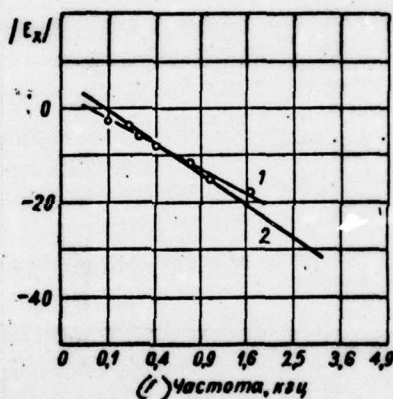
Fig. 10. Theoretical and experimental dependence horizontal component $|\dot{E}_x|$ electric intensity in the maximum of radiation pattern (in dB) relative to the level 1 μV/m as functions of frequency. 1 - experimental curve; 2 - theoretical curve.

Key: (1). Frequency, kHz.

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As noted above, during the shallow insertion of the transmitting and receiving antennas into the earth/ground the dominant role plays the side wave. Since in this case (unlike propagation through the layer of "basalt") the route of communication/connection does not have the shielding coating, it is subjected to the effect of the space, atmospheric and other interferences in the same degree as the ground communication lines. In the range of frequencies 15-150 MHz the fundamental interferences create cosmic noises [121], as source of which is galactic noise. At frequencies below 15 MHz dominant role begin to play atmospherics (produced in essence by lightning discharges) and fields of jamming stations. It is necessary to accept into consideration not only local thunderstorms, but also the thunderstorms, moved away to tens thousand of dynamometers. The spectrum of the latter in essence is determined by the conditions of radiowave propagation. The consequence of this is that the level of atmospherics at night higher than in the daytime (Fig. 11a and b), and the maximum of spectral distribution is arranged in region 8-10 kHz. In the range of frequencies below 1 kHz the significant role exerts the Sun the moon, which induce terrestrial currents [121].

The analysis showed that atmospherics have the horizontal component of electric field, much smaller than vertical component.

Therefore the majority of the researchers [118, 124, 145, 146] measured the vertical component. With underground radio communication are more profitable to conduct method horizontal the components of the electric field of signal, and means for our purposes is necessary the account of the precisely horizontal component of the electric field of atmospherics. Was designed [by 121] their linear weakening because of absorption in the earth/ground during propagation depthward. Data of the calculation are given in table.

Figure 11a and b gives borrowed from [96] the curve/graph of the spectral distribution of the horizontal component of the electric field of atmospherics of the surface of the Earth in the area of south California in winter in daytime and night time.
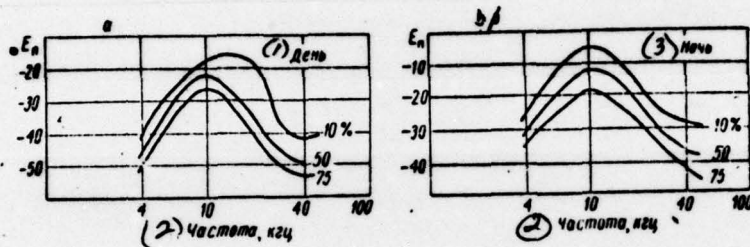
Fig. 11. Spectral amplitude distribution of the horizontal component of the electric field of atmospherics E_n (in dB) relative to level 1 μV/m of the surface of the Earth during December 1959 in California. a - day; b - night. Passband of receiver - 100 Hz.

Key: (1). Day. (2). Frequency, kHz. (3). Night.

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Curves show the noise field intensity at different frequencies, which is exceeded by the indicated in figures percentage of time. In this same article [96] are data on the integral distribution of the horizontal component of the electric field of atmospherics. In the

territory of the USSR the greatest interference level is observed in southern latitudes, and minimum - in polar regions. the selection of carrier frequency it is necessary to produce, by taking into account not only the condition of the creation of the maximum strength in receiving antenna (see §4), but also the spectral field distribution of interferences.

The preliminary analysis showed [152] that to 25o/o of area of the USA it is possible to carry out radio communication through the "basaltic" waveguide up to distances more than 65 km. Communication/connection with the use of a side wave (antenna of deep insertion) is possible at a distance to 1600 km.

In conclusion the authors consider their pleasant duty to express appreciation to G. A. Ostroumov and L. B. Lasanenko, who made a series of useful observations about content of article.

Linear weakening of the interferences of different frequency in the earth/ground with electrical conductivity 10^{-2} 1/ohm•m.

(1) Частота, гц	(2) Ослабление, дб/м
10^2	0,0171
10^3	0,0545
10^4	0,171
10^5	0,545

Key: (1). Frequency, Hz. (2). Weakening, dB/m.

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