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Translation

MARINE ELECTROMAGNETIC RESEARCH. COLLECTION OF THE INSTITUTE OF TERRESTRIAL MAGNETISM, THE IONOSPHERE AND RADIO WAVE PROPAGATION OF THE USSR ACADEMY OF SCIENCES

Ed. by

G.A. Fonarev

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[Edited by Gennadiy Aleksandrovich Fonarev, Candidate of Physico-Mathematical Sciences]

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ANNOTATION

Articles in this collection are devoted to studies of the electromagnetic fields of sea waves, certain aspects of magnetotelluric sounding and analysis of anomalous magnetic fields. The collection is designed for specialists working in the field of studying electromagnetic phenomena in the seas and oceans.

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VERTICAL COMPONENT OF THE ELECTRIC FIELD INTENSITY INDUCED BY THE MOTION OF SEA WATER

[L. M. Abramova, V. N. Mitrofanov, S. A. Skryabin, pp 3-10]

The vertical component of the electric field E_z induced by the motion of sea water in the geomagnetic field B occupies a special position in the studies of the electric field of a hydrodynamic source and the dynamics of the source itself. This arises from the existence in the sea of a sharp conductivity boundary: the "seawater-air" boundary. The component E_z, in the general case, in the center of large-scale movements does not depend on the conductivity distribution or the configuration of the motion, being a function only of the local velocity and horizontal component of the earth's magnetic field [1].

$$E_z = V_x B_y - V_y B_x , \qquad (1)$$

V_{xy} are the velocity components of the sea water.

Young, et al. considered this fact for the first time, as indicated in reference [2]. Later this component was used to study the speed of movement of sea water [3, 4]. For sea waves E_z was presented in [5], where the solution for the electric field potential of a two-dimensional progressive wave obtained in reference [1] was used. For the analysis and estimates of E_z the above-indicated authors either investigated the two-dimensional model of motion or it was assumed that the meter was placed at the middle of the flow.

The more general solution by comparison with the preceding one for E_z was obtained by D. Sanford [6] for the class of movements, the horizontal dimensions of which are much greater than the vertical nonuniformities. In particular, he studied the model in which there is only a horizontal velocity component V_{xy} (the vertical velocity component is assumed to be negligibly small by comparison with the horizontal one), which is entirely acceptable for a large class of large scale movements of the sea and waves in shoal water.

The vertical component of the electric field is expressed as follows:

$$E_z = V_x B_y - V_y B_x - \frac{\partial}{\partial x}\int_z^0 B_z(V_y - \bar{V}_y)d\xi + \frac{\partial}{\partial y}\int_z^0 B_z(V_x - \bar{V}_x)d\xi \qquad (2)$$

where $\bar{V}_{xy} = \frac{1}{D}\int_{-H}^0 V_{xy}\, d\xi$ is the speed averaged with respect to depth considering the

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conductivity of the sediments -- the effective speed. $D = H + (\sigma_2/\sigma_1)(H_s - H)$ is the average depth of the sea considering the conductivity of the sediments -- the effective depth of the sea. H is the depth of the sea, H_s is the thickness of the layer of sediments, σ_1 is the conductivity of sea water, σ_2 is the conductivity of the sediments.

For potential velocity distribution (or at the center of symmetric distribution) expression (2) becomes (1), that is, it is the sum of two terms, the ratio of which depends only on the direction of motion of the sea water. This expression, as was pointed out above, is validly used in practice when studying large-scale movements when the velocity distribution is sufficiently stable and known.

In the case of wind waves the velocity distribution is of a random nature, and the dimensions of the source are small by comparison with the measurement bases; it is also necessary to consider the last two terms in expression (2) which depend on the vertical component of the main magnetic field of the earth, B_z.

For a more detailed study of the distribution of E_z in the waves in the coastal zone of the sea, let us consider the specific problem with the following velocity distribution:

$$\begin{aligned} V_x &= i V_{ox} \cos \ell y\, e^{i(kx-\omega t)} f_x(z), \\ V_y &= -V_{oy} \sin \ell y\, e^{i(kx-\omega t)} f_y(z), \\ V_x &= V_y = 0 \quad \text{for: } |y| > \frac{\pi}{2\ell}. \end{aligned} \tag{3}$$

This distribution is characterized by the fact that the velocity components along the crest (the y-coordinate) and along the wave propagation (the x-coordinate) have different damping laws with respect to depth. The existence of such distribution obviously is realistic [7]. For this model of a wave expression (2) is represented in the following form:

$$\begin{aligned} V_z e^{-i(kx-\omega t)} &= i V_{0x} [B_y f_x(z) \cos \ell y - \ell B_z f_{1x}(z) \cdot \sin \ell y] \\ &+ V_{0y} \sin \ell y [B_x f_y(z) + i k f_{1y}(z)], \end{aligned} \tag{4}$$

where $f_{1xy} = \frac{z}{D+H}\int_{-H}^{0} f_{xy}(\xi)d\xi + \int_{z} f(\xi)d\xi$.

From formula (4) it is obvious that as a result the characteristic features of the electrodynamic solution, the functions f(z) and $f_1(z)$ have significantly different dependence on depth: namely,

on the surface, z = 0

$$f(z) \neq 0, \quad f_1(z) \equiv 0$$

on the bottom z = -H

$$f(z) \neq 0, \quad f_1(z) \neq 0.$$

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From this condition it follows that in the general case on the surface of the sea the vertical component of the electric field E_z is defined only by the horizontal component of the field B_{xy}, and on the bottom, by the sum of two terms, one of which arises from the vertical component of the magnetic field of the earth B_z, and the other, the horizontal component B_{xy}. Inasmuch as for one term of the expresson (4) there is no imaginary factor, the phase E_z will depend on the relation of the velocity components, depth and position of the point of measurement with respect to the crest. In the middle of the crest (y = 0) the phase E_z is constant with respect to the entire depth; for other values of y the phase varies with respect to cross section.

Depending on these factors, the magnitude of the measured signal, that is, the contribution from each term of expression (4), will vary. The ratio of the contributions of the horizontal and vertical components of the earth's magnetic field in E_z is defined by the ratio of these components of the geomagnetic field, and it also depends on the characteristic dimensions along the crest $\pi/2\ell$, the coordinate z (the observation horizon) and the contribution of the conducting sediments.

For the velocity V_x directed along the meridian the contribution to E_z will occur only as a result of the vertical component of the earth's magnetic field, B_z, where it will be the most significant, of course, at high latitudes, on the magnetic equator with this direction of the wave motion $E_z \equiv 0$.

In the case of latitudinal direction of the velocity and large values (high geomagnetic latitudes), the contribution as a result of the two components can be commensurate in a wave of equivalent dimensions with respect to wave length and crest length, especially on the horizons ~H/2. In the middle and low latitudes the primary contribution is made by the part E_{z1} caused by the horizontal component of the primary magnetic field of the earth.

In the case of a pure "wave current" where the velocity is uniform to the bottom, that is, f(z) = const = f, and $V_y = 0$,

$$E_z = i f V_{0x} [B_y \cos \ell y + (1 - \frac{H}{D}) B_z \sin \ell y], \tag{5}$$

that is, the vertical component of the electric field E_z of the "wave current" is equal to zero on the surface, is maximal at the bottom and has constant phase.

Let us consider this phenomenon in the example of the electric field of sea waves. In 1973 in the vicinity of the port of Mirnyy (the Crimea) experimental studies were made of an electromagnetic field of a hydrodynamic source.

The vertical component of the electric field of sea waves was measured by two static meters with silver chloride electrodes by the IZMIRAN-IELAN system. One vertical measuring base was located at the bottom, and the other near the surface (Figure 1). The length of each base was 1 meter; the distance between centers of the bases was ~2 meters. Both bases were located on the same vertical. Along with the electric field sensors was a wire wave meter for recording the wave height. The depth of the sea at the measurement point was ~5 meters. The recording of the electric field measured on the upper and lower bases and the wave height was made on one tape of the K-12-22 oscillographic automatic recorder. The mean amplitude E_z recorded by the upper meter was 40 to 60 microvolts per meter; the amplitude recorded by the

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lower meter was 30 microvolts per meter, and the average oscillation period T ~ 5 seconds. The vertical component was measured during stormy weather.

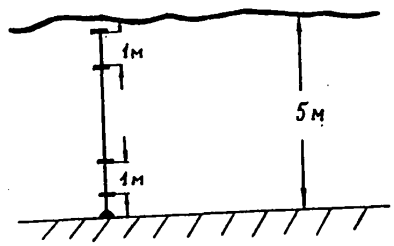

Figure 1.

A characteristic feature of the recorded vertical fields is the presence of a significant phase shift between the upper and lower field meters. The phase fluctuates from 60° to 120°.

For interpretation of the results of measuring the electric field E_z of the wave action, as an example let us consider the model of a wave with crest of finite length and with a specific velocity damping law with respect to depth. We shall consider only one velocity component V_x of the type:

$$V_x = V_0 e^{i(kx-\omega t)} \cos \ell y \frac{ch\, k'(z+H)}{ch\, k'H}, \tag{6}$$

where $k' = \sqrt{k^2 + \ell^2}$. This model approximates the wave motion in shallow water when $H < \lambda/2$.

In this case

$$E_z = E_{z1} + E_{z2}; \qquad E_{z1} = F_y V_x;$$
$$E_{z2} = -F_z V_0 \frac{\ell}{k} \sin \ell y e^{i(kx-\omega t)} \{ th\, k'H - \frac{sh\, k'(z+H)}{ch\, k'H} + \frac{z}{D} th\, k'H \}. \tag{7}$$

The pair of electrodes located near the surface recorded the field amplitude E_z caused actually by the first term E_{z1}. For estimation of the ratio of the signals measured on the bottom and on the surface, let us give the actual values of: $V_0 = 2$ m/sec, $F_y = 0.2 \cdot 10^{-4}$, T = 5 sec, $k \approx 0.2$, $\ell \sim 0.06$, D = 30 meters. Then on the surface, $z \approx 0$

$$E_z = E_{z1} = F_y V_x = 40 \cos \ell y e^{i(kx-\omega t)} \text{ (microvolts/meter).}$$

The second pair of electrodes located near the bottom, z = H measured the following:

$$E_{z1} = V_0 F_y \cos \ell y e^{i(kx-\omega t)} \frac{1}{ch\, k'H} \cong 24 \cos \ell y e^{i(kx-\omega t)} \text{ (microvolts/meter);}$$

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$$E_{z2} = -V_0 F_z \frac{\ell}{k'} \sin \ell y e^{i(kx-\omega t)} \left\{ th\, k'H - \frac{H}{D} th\, k'H \right\} = -13{,}2 \sin \ell y e^{i(kx-\omega t)}$$ microvolts/meter).

The sum of the component E_z on the bottom will give an oscillation with an amplitude of ~27 microvolts shifted in space along the crest with respect to E_z on the surface by an angle $\phi \cong 60°$. The amplitude ratio of the field on the surface and on the bottom

$$\frac{E_{z\ surf}}{E_{z\ bottom}} = 1.5.$$

According to the experimental data, the average value of this ratio will be ~2.0. The scattering can be explained, on the one hand, by the arbitrary choice of the parameters k and ℓ and the field F_y (since the direction of wave propagation was determined approximately); and on the other hand, by the fact that in real three dimensional waves the damping coefficient obtained by the experimental data presupposes faster damping of the orbital velocity with depth [8].

The magnitude of the phase shift and the amplitude ratio E_z near the bottom and near the surface are defined obviously by all the terms of expression (4); for more exact estimation of these values it is necessary to know the real velocity distribution in the wave and the location of the meter with respect to the wave.

By the surface measurements of E_z, the order of magnitude of the peak value of the velocity component in the east-west direction $|V|_{east-west}$ was estimated:

$$|V|_{\text{в-з max}} = \frac{E_z}{F_y} = \frac{(40-60)\cdot 10^{-6}}{0.2\cdot 10^{-4}} = 2-3$$ m/sec.
(a)

Key: a. east-west max

This is an entirely realistic value for the speed in shallow water during a severe storm.

In conclusion, it must be noted that inasmuch as the solution (2) which we took from [6] was obtained for the steady state problem with one restriction — the characteristic horizontal dimensions of the source are much greater than the effective depth of the ocean -- the study made in this article is valid for an entire class of sea movements satisfying this condition: currents, tides, long rolling seas and tsunami on the shelf and wind waves in the coastal zone.

In the case of measuring the electromagnetic field which can be considered as a random process, it is necessary to consider that not only the magnitude, but also the phase of the recorded components depends upon the position of the meter with respect to the investigated wave.

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DETERMINATION OF THE CONDUCTIVITY OF SEDIMENTS BY MEASURING THE ELECTRIC AND MAGNETIC FIELDS AND WAVE VELOCITY COMPONENTS AT THE BOTTOM OF THE SEA

[L. M. Abramova, pp 11-14]

Electromagnetic fields induced by the movement of sea water in the geomagnetic field are used in oceanography to obtain detailed information about the velocity structure of the ocean movements which sometimes is very difficult if not in general impossible to obtain by other methods.

Another aspect of using a hydrodynamic source is the study of the deep structure of the earth, for the fields induced by it depend on the conductivity, the thickness of the sediments and the distance to the conducting mantle. The effort to use this source to determine the depth to the conducting mantle was made by Larsen [1] by the method of magnetotelluric sounding. Teramoto proposed a method of determining the effective conductivity of the bottom of the channel by measuring the potential difference across the channel, the electric current density and the speed of the water [2]. By using this method a zone of anomalous conductivity was isolated under the Sangarskiy Strait[1], which is a continuation of the conductivity anomaly observed in Japan.

In the indicated papers a study was made of a uniformly layered model made up of the conductivities of the ocean σ_1, the sediments σ_2, the nonconducting crust and highly conducting mantle σ_m [1, 2].

The influence of the mantle on the induction mechanism depends on the ratio of the linear dimensions of the hydrodynamic source L and the skin depth of the mantle δ_m at the frequency ω. The electromagnetic frequency wave penetrates the mantle to a depth $\delta_m = (2/(\mu, \omega, \sigma_m)^{1/2}$.

When $\delta_m/L >> 1$ it is possible to neglect the mantle; for $\delta_m/L << 1$ it is necessary to consider the effect of the mantle when estimating the conductivity.

In this paper a method is proposed for determining the effective conductivity of the sediments by measurements of the electric and magnetic fields and the velocity components at the bottom. Here the class of movements for which $\delta_m/L >> 1$ can be used as the sounding source. This includes the wind-driven waves and swell in shallow water, the stationary and certain other movements for which the contribution of the mantle to the mutual induction process between the ocean and the mantle is negligible.

[1]Tsugaru Strait.

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Let us consider a model of the ocean movement with three-dimensional velocity distribution with respect to the x, y and z coordinates.

In general form the components of the electric and magnetic field induced by the movement of the sea water in the model with three-dimensional velocity distribution, according to the solution of Sanford [3] are expressed as follows:

$$E_x = F_z V_y^* + j_x/\sigma_1 , \tag{1}$$

$$E_y = -F_z V_x^* + j_y/\sigma_1 , \tag{2}$$

$$B_x = \mu \sigma_1 F_z V_x^* (D-H) + \frac{\mu D}{2}\left(1 - \frac{2H}{D}\right) j_y , \tag{3}$$

$$B_y = \mu \sigma_1 F_z V_y^* (D-H) + \frac{\mu D}{2}\left(1 - \frac{2H}{D}\right) j_x , \tag{4}$$

where j_{xy}, E_{xy} and B_{xy} are the components of the electric current, the field and magnetic field, respectively; F_z is the vertical component of the geomagnetic field, μ is the magnetic permeability, σ_1 is the specific conductivity of sea water $V^*_{xy} = (1/D) \int_{-H}^{0} V_{xy} d\xi$ is the average velocity with respect to depth considering the conductivity of the sediments -- the effective velocity $D = H(I + \gamma)$ -- the "effective" depth to which the induced current penetrates (considering the conductivity of the sediments), $\gamma = S_2/S_1$ is the ratio of the longitudinal conductivities of the sediments S_2 and the sea water S_1, and H is the depth of the sea.

Expressing j_x and j_y from (1) and (2) and substituting in (3) and (4), we obtain the value of the parameter γ -- the ratio of the integral conductivities of the layer of sediments and sea water:

$$\gamma = 1 + \frac{F_z V_x}{E_y} - \frac{2 B_x}{\mu \sigma_1 H E_y} = 1 + \frac{F_z V_y}{E_x} - \frac{2 B_y}{\mu \sigma_1 H E_x} . \tag{5}$$

Having data available from bottom measurements on V_{xy}, E_{xy} and B_{xy}, it is possible to estimate the total longitudinal conductivity of the sediments $S_2 = \gamma S_1$.

In the case of a model with one velocity component, for example, V_x, the parameter γ will be determined from the expression:

$$\gamma = 1 + \frac{F_z V_x}{E_y} - \frac{2 B_x}{\mu \sigma_1 H E_y} . \tag{6}$$

The parameter S_2 as applied to the induction problems of wind-driven waves is quite provisional in the geophysical sense, for the linear dimensions of the source can be less than the layer of sediments; in this case S_2 defines the effective conductivity of the part of the sediments to which the current is closed. For long rolling seas, meteorological fluctuations, and so on, the linear dimensions of which are commensurate with the thickness of the layer of sediments, this parameter determines the effect of the entire layer.

The contribution of the conducting sediments to the process of electromagnetic field induction as a result of the waves was estimated by the synchronous recordings

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obtained during bottom measurements of the magnetic field B_x, electric field E_y and velocity components V_x of the wind-driven waves. The depth of the sea at the time of the measurements was 1.2 to 1.5 meters [4]. The vertical component of the earth's magnetic field in the measurement zone was $0.52 \cdot 10^{-4}$ tesla.

By formula (6) an estimate was made of the parameter $\gamma = S_2/S_1$. The mean values of the amplitudes obtained in the time interval of ~100 seconds were taken for the calculations: V_x = 2.3 m/sec, $E_y = 8.4 \cdot 10^{-6}$ volts/meter, B_x = 1.2 ntesla. The corresponding value turned out to be equal to 18. If we take the total longitudinal conductivity of sea water $S_1 = \sigma_1 H$ = 4.8 to 6 (moh), it is possible approximately to estimate the effective longitudinal conductivity of the part of the sediment layer through which the currents are closed

$$S_2 = \gamma S_1 = 18 \cdot (4,8 \div 6) = 86 - 108 \text{ (moh)}$$

The correctness of the estimate was confirmed by the results of the spectral analysis of these materials when for the given a priori hydrodynamic model, the spectra of the electric field components were calculated by the measured velocity spectra. The spectra calculated considering the value of S_2 demonstrated good agreement with the experimentally obtained estimates of the spectral densities of the electric field. What has been stated here again confirms that the wave movements of the field can be an additional source for studying the deep structure of the earth.

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STATISTICAL CHARACTERISTICS OF THE RELATION OF THE WAVE PARAMETERS TO THE INDUCED ELECTROMAGNETIC FIELD

[Yu. M. Abramov, L. M. Abramova, pp 15-21]

Up to the present time, judging by the published papers only a small number of studies were made including simultaneous recording of the parameters of the velocity field of sea waves and electric and magnetic fields induced by the wave movements. The small number of such studies is explained by difficulty in stating the complex measurements at sea, including the absence of special electromagnetic marine equipment.

Complex studies of the electromagnetic fields of the waves in the coastal zone have been performed at the IZMIRAN SSSR [Institute of Terrestrial Magnetism, the Ionosphere and Radio Wave Propagation of the USSR Academy of Sciences] since 1971. In the given paper the results are presented from full-scale studies of electromagnetic fields of waves, the purpose of which was establishment of the statistical relations between the characteristics of the electromagnetic and hydrodynamic fields of the waves.

The components of the electric and magnetic fields of the wave action and the hydrologic parameters -- the wave velocity and height -- were recorded in the coastal zone of the White Sea (the vicinity of Cape Abramovskiy).

The measurement procedure is described in [1]. As a result of this study, synchronous recordings were obtained for three components of the magnetic field of the waves B_x, B_y, B_z, two horizontal components of the electric field E_x and E_y and also the hydrologic parameters -- the shift of the free surface $h_w = 2A$ (A is the wave amplitude) and the velocity component normal to the shore, V_x.

When processing on a computer, the recording was usually made at increments of 0.5 to 0.6 second.

The statistical characteristics of the distribution, the mutual correlation and mutual spectral functions and also the coherence functions were calculated.

The statistical parameters obtained during the processing (the excess and asymmetry coefficients of the distribution functions of the y-axes of the wave height recordings, velocity and parameters of the electromagnetic wave) demonstrated that in the first approximation usually the hypothesis of normal distribution is applied.

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An example of one of the mutual correlograms characterizing the relation of the parameters E_x and h_w is illustrated in Figure 1.

All of the mutual correlograms have the form of functions that damp to the 0.1 level from the maximum value in 10-20 seconds.

The form of the correlograms indicates that in both processes there is a quasiperiodic component present with a period of 5-6 seconds which is typical for wind-driven waves. The processes are close to the so-called narrow-band processes with characteristic periods related to the frequency ω_0, near which the maximum energy of the process is concentrated.

For all of the mutual correlograms characterizing the relation of the components of the electric field (E_x, E_y) and the hydrodynamic parameters (V_x, 2A) the presence of a shift of a maximum of the mutual correlation function is typical, indicating the existence of a phase difference of the oscillations of these components. The degree of the relation of the electric field component E_y and the velocity parameters (the wave height) is low, and the mutual correlation factor r_{xy} = 0.5. The small magnitude of the mutual correlation coefficient of these parameters obviously is explained by the fact that the measurements were taken not at one point, but they lay on a straight line not coinciding with the general direction of motion of the wave front. As for the degree of the correlation of the components $E_x - V_x$, it appears to be closer, $r_{xy} \sim 0.7$, and this is explained by the fact that the meters for measuring these parameters were located in practice at one "point," which revealed better interrelation of the processes.

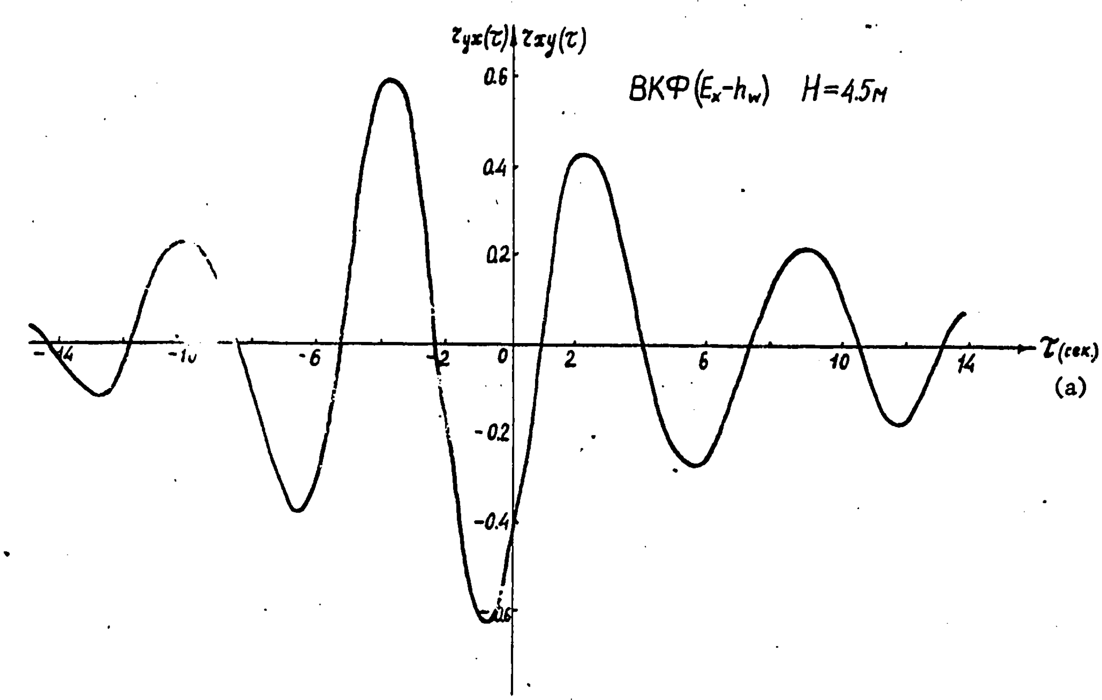

Figure 1.

Key: a. τ, sec

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Mutual correlation analysis of the hydrodynamic and electromagnetic parameters did not demonstrate a sufficiently convincing relation between the processes in the time region, which is explained by imperfection of the measurement procedure. The results of spectral analysis, however, indicate the presence of a clear relation between the investigated processes and the frequency region. A comparison of the velocity spectrum (just as the wave height) with the spectra of the components of the electric and magnetic fields demonstrated that in accordance with linear theory, there is good similarity of these characteristics in the spectral sense, Figure 2 a, b.

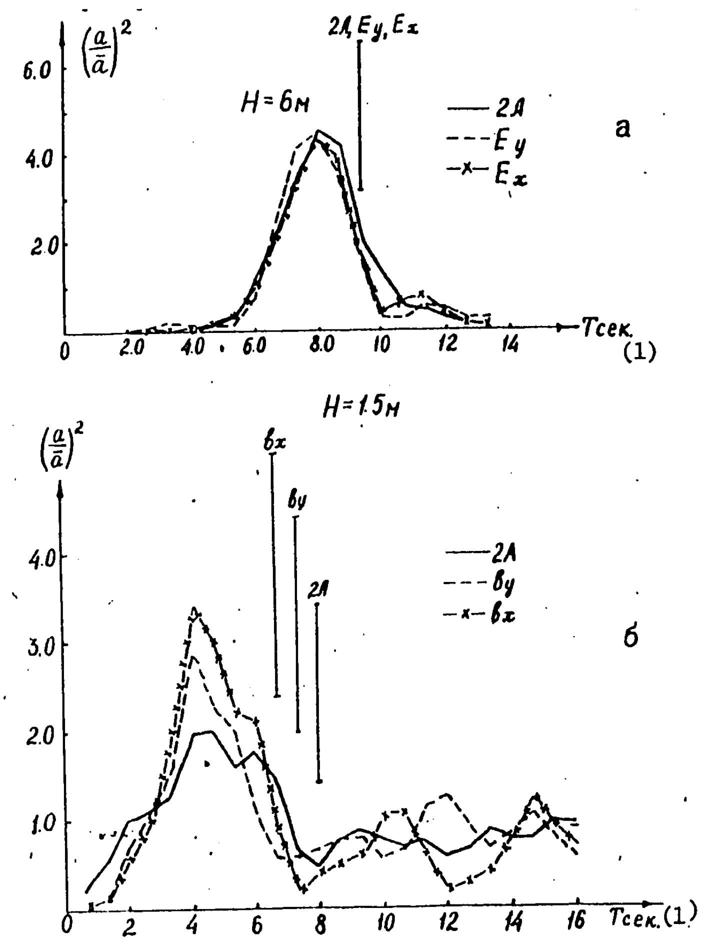

Figure 2

Key: 1. second

The curves for the estimates of the spectral density functions of the wave height 2A, the velocity V_x and the electric field components E_x and E_y have basic peaks at the periods of the wind-driven waves. The peaks are well expressed and coincide with each other. In the estimates of the spectral densities there are additional peaks

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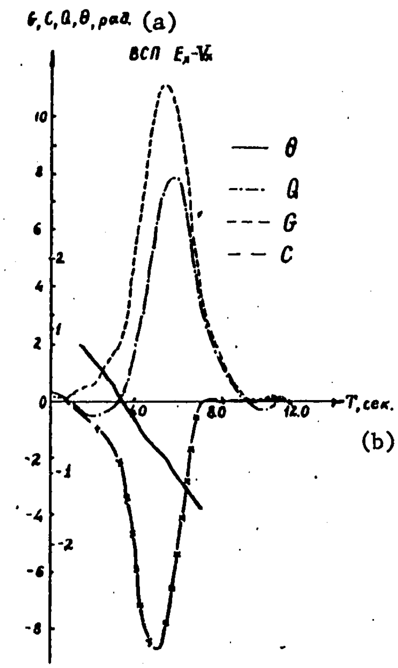

Figure 3.

Key: a. radians b. second

at the periods close to the basic period which are lower with respect to amplitude, but coincide with each other for all components.

The presence of a relation between the electromagnetic field and the velocity field parameters in the frequency region also confirm the calculated mutual spectra for these parameters. Figure 3 illustrates the mutual spectrum of the components E_x – V_x, $S_{xy}(\omega)$.

The wave frequency is plotted on the x-axis, and the mutual spectrum characteristics are plotted on the y-axis:

G is the mutual spectral density function,

C is the cospectrum,

Q is the quadrature spectrum,

Θ is the phase shift between components.

The graphs of the components of the mutual spectra indicate that the energy exchange between the investigated components takes place primarily in the range of periods of 4–8 seconds corresponding to the wind-driven waves. On the remaining periods, the energy exchange is insignificant. The nature of the phase curves is different for

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different components, which is explained by the separation of the observation points in space.

The coherence of the investigated parameters is high; its peaks come on the same frequencies as the spectral density and mutual spectral density peaks. Figure 4 shows the coherence functions $F^2(\omega) = |S_{xy}(\omega)|^2/S_x(\omega)S_y(\omega)$, $0 \leq F^2(\omega) \leq 1$ as a function of the wave period calculated for the electric field components, velocity and wave height.

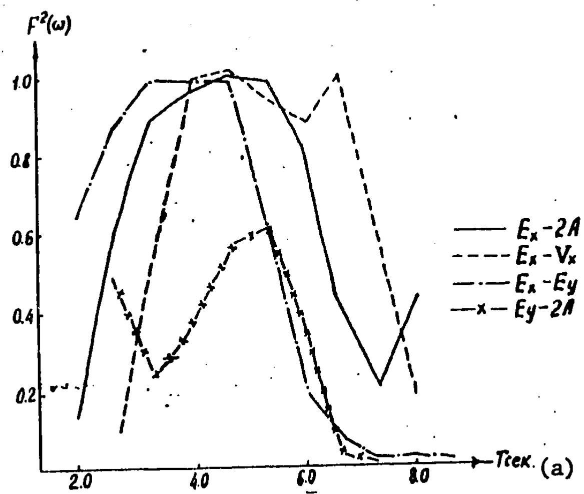

Figure 4.

Key: a. T, seconds

The investigated results of the spectral analysis of the parameters of the hydrodynamic and electromagnetic wave fields under various meteorological conditions indicate that there is a clear and stable spectral relation between these parameters. This again confirms that the electromagnetic fields are a sufficiently exact representationof wave hydrodynamic processes in the sea.

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COMPLEX MEASUREMENTS OF ELECTROMAGNETIC FIELDS OF WAVES IN THE COASTAL ZONE. (RESEARCH PROCEDURE AND SOME RESULTS)

[Yu. M. Abramov, L. M. Abramova, S. M. Minasyan, V. N. Mitrofanov, A. S. Shcherbakova pp 22-40]

At the present time marine electromagnetic measurements are acquiring great significance in the overall complex of marine geophysical research.

In spite of their obvious urgency, the measurements of the variable electromagnetic field widespread for dryland research has still not received sufficient development under marine conditions. The reason for this lies primarily in the fact that during experimental studies in the sea difficulties arise connected with the sealing of the measuring equipment, its stabilization on a moving platform (buoy and floating station) and chemical agressiveness of sea water. In addition, the studies of the electromagnetic variations in the sea are complicated by the appearance of an additional source of a variable electromagnetic field -- a hydrodynamic field caused by movement of the conducting sea water in the magnetic field of the earth.

The most powerful interference when studying the morphology of the variations in the sea in the short-period part of the spectrum are the electromagnetic fields of wind-driven waves and swells.

The data from theoretical calculations and experimental measurements indicate that the maximum amplitudes of the electromagnetic fields of sea waves have values from tenths to units of gammas in the magnetic field and from tenths to hundreds of millivolts per kilometer in the electric field in the range of periods of 1-40 seconds, which is entirely commensurate with the electromagnetic fields caused by an ionospheric source in the same frequency range (short-period oscillations) and even exceeds them. The structure of the distribution of these fields in the water and in the air has a complex nature connected with the conditions of the movement of waves in the world ocean, the conductivity distribution in the ocean and sediments, the depth of the ocean, and so on.

The electromagnetic fields induced by a hydrodynamic source can have a significant effect on the operation of marine electronic reconnaissance gear of the electromagnetic current meter (EMIT), lowering the reliability of the measured values. On the other hand, the induced fields as a function of conductivity, thickness of the sediments and distance to the conducting mantle, offer the hope for future use of electromagnetic fields of the hydrodynamic source to study the geoelectric section [1].

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It is no less important to study the electromagnetic fields of hydrodynamic origin in the interests of oceanography. At the present time the EMIT [electromagnetic current meter] is widely known and is finding practical application in oceanography. The electromagnetic fields of wind-driven waves and swells can also be used to study the nature and the characteristic features of their source.

The enumerated factors indicate the urgency of setting up theoretical and experimental studies of electromagnetic fields of wind-driven waves and swell.

The small number of experimental studies of these phenomena is connected with the difficulty of setting up this type of measurement at sea. The wind-driven wave and swell fields attenuate rapidly with depth; there is an alternative -- either to stabilize the measuring elements in the hydrodynamic field when performing measurements at the source or remove the sensors from the source, increasing the sensitivity of the measuring device. Both alternatives still run into technical and procedural difficulties. On the existing level of measurement equipment and means of setting it up in the sea, reliable measurements of the electromagnetic fields of sea waves can be taken most successfully under shoal water conditions. Technically it is easier to measure the magnetic and electric fields of waves in shoal water; both scalar and component sensitive elements can be used with the same degree of success here, for they are installed on the bottom. The advantage of measurements under these conditions is the possibility of using differential devices permitting isolation of the wave fields in "pure" form. For this purpose one measuring sensor is placed in the range of the electromagnetic fields of the waves, and the other at a considerable distance from the source, on land. In the absence of noticeable geomagnetic variation field gradients of external sources, the difference of the signals of these sensors is proportional to the electromagnetic field of hydrodynamic origin. In addition, for certain wavelengths in the short-period part of the spectrum, even a shallow sea ($H \sim 5$-7 meters) can be considered as "deep" ($H > \lambda/2$), which permits use of short wind-driven waves as a micromodel of long rolling seas in deep water.

In the USSR and abroad there are a quite large number of magnetometric and electrometric devices for recording variable electromagnetic fields on the dry land under stationary conditions. The specific nature of the operation of the meters under marine conditions as part of buoy, bottom and floating stations limits the possibilities of the application of this equipment, especially when measuring components [2].

The basic requirements on the equipment for measuring the electromagnetic fields of sea waves with respect to resolution (0.01 to 1 μ in a magnetic field and 0.1 to 10 microns/m in an electric field) and frequency range (1-0.03 hertz) demonstrate that such observations can be made using the device for measuring electromagnetic field variations in the sea.

In this paper primarily the results of measuring the electromagnetic fields of sea waves are considered which were obtained on an expedition for complex investigation of variable magnetic fields in the vicinity of Cape Abramovskiy in the White Sea in 1973.

Taking measurements of the electromagnetic fields of sea waves in this region was complicated by the fact that it is in a zone of increased magnetic activity. On the other hand, the advantage of measurements at high latitudes is that

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basically only the vertical component of the earth's primary magnetic field is present, which simplifies interpretation of the data obtained and the choice of models.

The region in which the measurements are taken is characterized by a flat coastline with a slope of 1-2° directed from west to east. At this location the syzygial tides have a height on the order of 7 meters, and the quadrature tides 6 meters, and they have a strict semidiurnal nature.

The diagram for deploying a set of measuring equipment is presented in Figure 1. At maximum low tide the depth of the sea at the point of installation of the sensors is 1 meter, and the distance to shore at low tide is 300 meters.

The electric potential differences were measured by static meters on two mutually perpendicular bases by 5 silver chloride electrodes of the IZMIRAN-IELAN system. Different combinations of these electrodes made it possible to select the length of the measuring bases equal to 10 or 20 meters. The signal from the electrodes traveled along a P-268 type cable to the recording equipment located on the shore. All of the measured values in this experiment were recorded on the 12-channel K-12-22 automatic recorder; the sensitivity of recording the potential differences was 0.03 mv/mm. The diagram of the installation of the electrodes in the sea is presented in Figure 2. In addition to measurements of the potential difference of the wave electric field, the potential method was used, the essence of which consists in the fact that one of the electrodes (the measuring electrode) is placed directly in the measured field, and the other ("zero") outside the range of this field. The signal picked up from the electrodes is in this case proportional to the potential of the measured electric field at the point of installation of the measuring electrode.

Inasmuch as the investigated signal varies synchronously in time with the speed of the wave relative to the measuring electrode, the component of the measured electric field parallel to the direction of this velocity is defined as follows:

$$E_x = \frac{\partial \varphi}{\partial x} = \frac{\vec{V}_\Phi \partial y}{V_\Phi^2 \partial t}, \quad (1)$$

where E_x is the electric field intensity component,

ϕ is the signal measured by the potential method,

$\vec{V}_\phi$ is the phase wave velocity with respect to the measuring electrode.

Lead plates 50 × 700 × 3 mm served as the zero electrode in the potential measurement method. They were dug into the ground a distance of 200-300 meters from the edge of the water on the land.

The magnetic field components of seawaves were measured by a ferrosonde three-component magnetometer installed on the bottom. The "y" component sensor was set up perpendicular to the meridian and parallel to the shore; the "x" sensor was set up in the direction of the meridian and perpendicular to the shore, and the "z" sensor, vertically.

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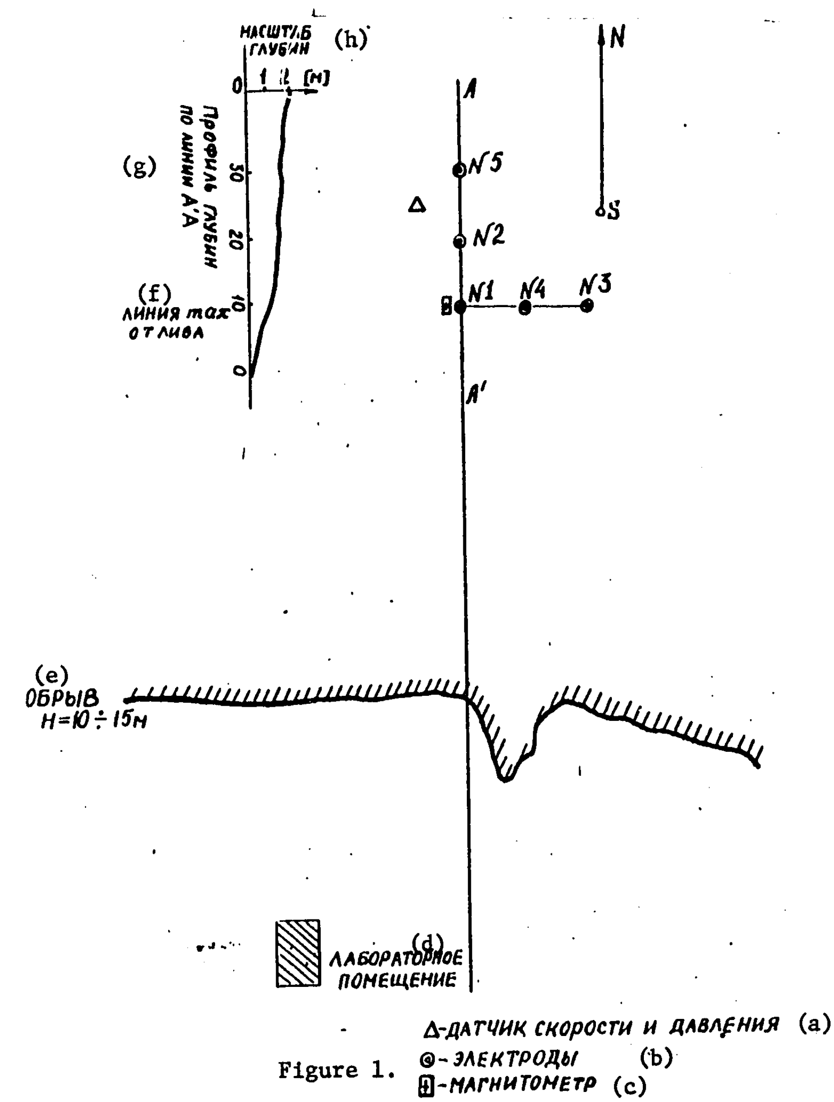

Figure 1.

Key:
- a. laboratory facility
- b. speed and pressure gage
- c. electrodes
- d. magnetometer
- e. scarp H = 10-15 meters
- f. maximum low tide line
- g. depth profile with respect to the A'A line
- h. depth scale

The general complex for measuring the magnetic field components was made up of the following:

1. SG-56 magnetometer with sensor,

2. compensator for the constant component of the earth's magnetic field,

3. connecting cable,

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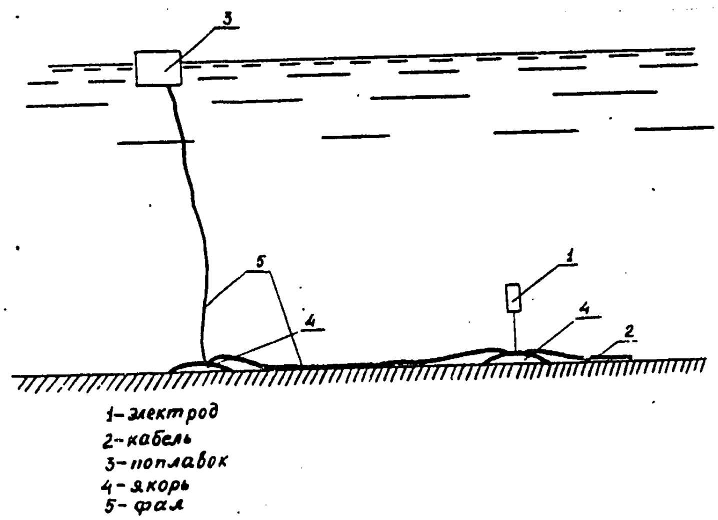

Figure 2.

Key: 1. electrode
2. cable
3. float
4. anchor
5. halyard

4. recorder,

5. power pack,

6. nonmagnetic container made of fiberglass.

The sensors of the magnetometer fastened orthogonally in a common frame and the magnetometer were placed in a sealed container. In turn, the container was fastened to a massive nonmagnetic slab and was put on the bottom from a boat at maximum low tide. The slab was held on the bottom by weights for greater stability. The signal from the magnetometer was transmitted over a KNSh-18 type cable to shore to the recording system. A composition current was fed over the same cable to the sensors.

The components x, y and z of the magnetic field were recorded with speeds of 6 mm/sec or 1.5 mm/sec. The magnetometer had the following scale divisions of the analog recording by components: $x = 0.52\ \gamma/mm$, $y = 1.0\ \gamma/mm$, $z = 0.48\ \gamma/mm$.

The measurements of the hydrologic parameters of the waves (velocity component normal to shore, V_x and wave height 2A) were taken by electrochemical converters converting the mechanical inputs to an electric signal.

In addition to the enumerated measurements when performing the operations, the meteorological and hydrological conditions in the vicinity of Cape Abramovskiy were observed and recorded by the hydrographic service of the meteorological station. Every three hours the following characteristics were recorded: the wind speed and direction, the average wave height, the nature and predominant direction of the waves, the water level at the measurement point. These data were taken into account when processing and analyzing the observation results.

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A crystal variation meter of the V. N. Bobrov system was set up on shore. The magnetic activity when measuring the electromagnetic fields of the waves was estimated by the readings of this meter.

As a result of the studies, synchronous recordings were obtained for the electromagnetic field components and the hydrodynamic parameters at different depths resulting from the tides. A sample recording is presented in Figure 3.

The procedure for processing the experimental data depends to a significant degree on the purposes and goals of the study. The following set of parameters was processed:

1. The electric potential differences $\Delta\phi$ on bases perpendicular and parallel to the shore (the electric field components E_x and E_y, respectively).

2. The wave potential at the point ϕ.

3. The magnetic field components B_x, B_y, B_z.

4. The velocity components of the water perpendicular to the shore, V_x.

5. The displacements of the free surface at a point, 2A.

In order to establish the amplitude-phase relations between different field components from synchronous recordings, the ordinates E, B, V, A were picked up, and the amplitude and phase relations were studied for pairs of these parameters.

When using the statistical method of interpretation of the results obtained, the recordings were deciphered by special standard curves. The volume of one realization included less than 80 to 100 wave periods [3]. The digitalization step size was selected as 0.5-0.6 second. The ordinates were reckoned from the base line.

The primary processing was done on the "Mir-1" computer by the programs of [4].

For each parameter of the electric, magnetic and hydrodynamic fields the statistical characteristics of the investigated processes were calculated: dispersion, mean square deviation, asymmetry coefficient, excess coefficient and their errors. These calculations demonstrated that both the hydrodynamic parameters and the characteristics of the electromagnetic field of the sea waves (periods and amplitudes) are subject to a normal distribution law on the whole.

Histograms and distribution curves of the wave heights, velocity and electromagnetic field which had been constructed by empirical data were used to study the statistical properties of the amplitude and period distribution of the investigated processes.

Let us first consider the amplitude distribution.

Figures 4-5 show the amplitude histograms of the components E_x, E_y of the electric field, the velocity V_x and wave height 2A for different depths of the sea H = 1.5 meter and 7 meters.

Ranges of values of the investigated element are plotted on the x-axis on the graphs, and the number of cases is plotted on the y-axis in percentages of the total number of terms of the series n (n = 300). The upper scale of the x-axis is

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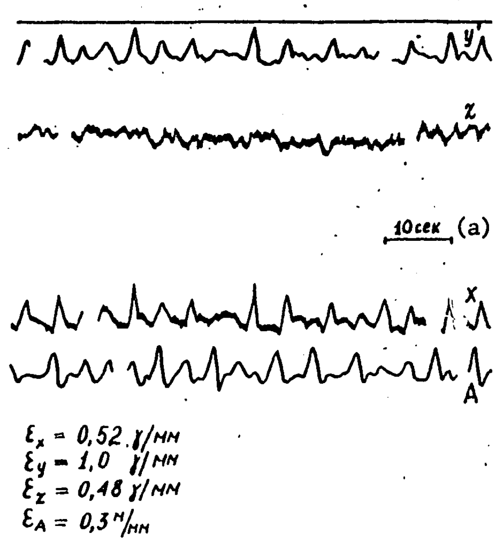

Figure 3.

Key: a. sec

the transformed distribution series, and the lower scale is expressed in units of the investigated element. The relations constructed on the basis of the histograms are the distribution or recurrence curves of the element.

Using the recurrence curve data, by successive summation of the number of cases, the x-axes of the integral distribution curve called the element guarantee curve in oceanography, were calculated and constructed.

The characteristic values of the investigated element are as follows: $\bar{y}$ is the mean value or center of distribution, $y_{50\%}$ is the value of the element with 50% guarantee, $y_{n=max}$ is the value of the element of greatest recurrence (mode); they permit determination of what type of distribution is characteristic of the given parameter. Thus, for $\bar{y} = y_{50\%} = y_{n=max}$, there is a symmetric distribution curve. Examples of the recurrence and guarantee curves of the electric field and velocity amplitudes for sea depths of 1.5 meters and 7 meters are presented in Figures 6 and 7.

Analogous calculations and constructions were performed for the periods of the electromagnetic field and hydrodynamic parameters, Figures 8-11. As is obvious from the histograms, waves are most frequently observed with periods of 2-4 sec. Such periods have the highest recurrence rate in the electric and magnetic field of the waves. The analysis of these curves must give answers to the following questions:

1. Does a relation exist between the amplitudes and periods of an electromagnetic and hydrodynamic field and in which components is it the closest.

2. How does the variation of the sea depth at the measurement point influence the properties of the distribution curves.

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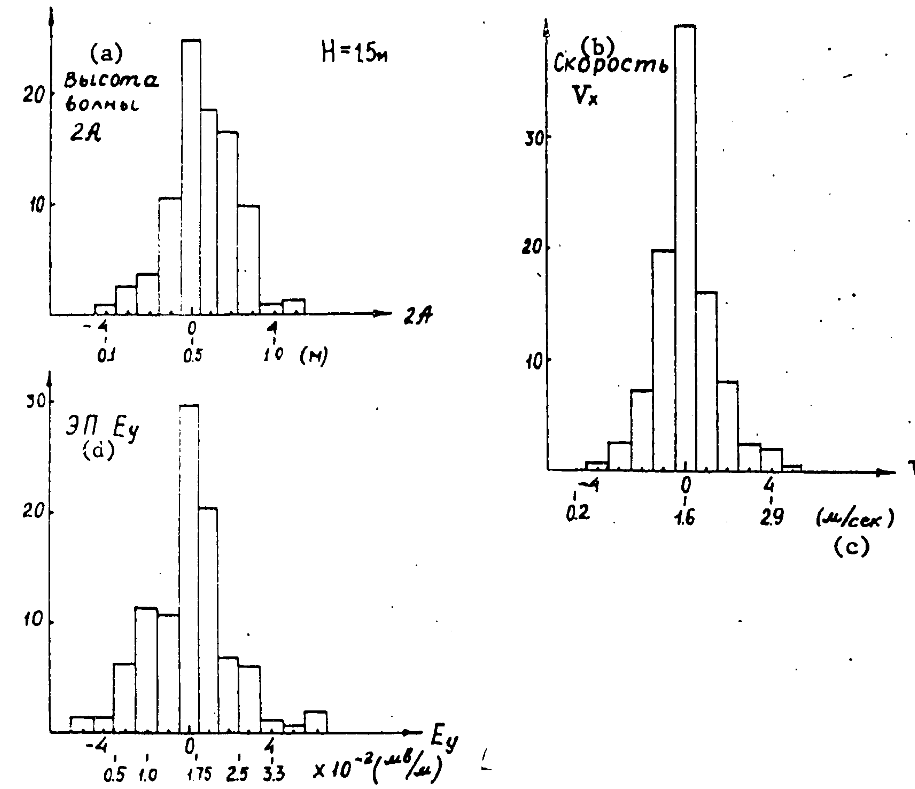

Figure 4.

Key: a. wave height
b. speed
c. m/sec
d. EP = electric field

An analysis of the histograms, the recurrence and guarantee curves for the amplitudes and periods indicates that the statistical relation exists and is quite reliable.

The peaks of the distribution curves with respect to amplitudes clearly coincide with each other, Figures 6-7. The amplitude distribution curves of the electric field and velocity are closest to each other. The peaks of the electric field and velocity distribution curves by periods do not coincide with each other. The peaks of the electric field distribution curves E_y, as a rule, are shifted somewhat in the long-period direction.

The estimates of the similarity of the distribution curves made by the Kolmogorov-Smirnov number λ demonstrated that with a probability $\alpha = 0.01$ all pairs of velocity and electric field distribution curves give values of the coefficient λ less than λ_{cr}, which indicates the presence of reliable similarity of these curves.

The distribution of the magnetic field components both by periods and by amplitudes is less clearly expressed by comparison with the other elements. This is explained

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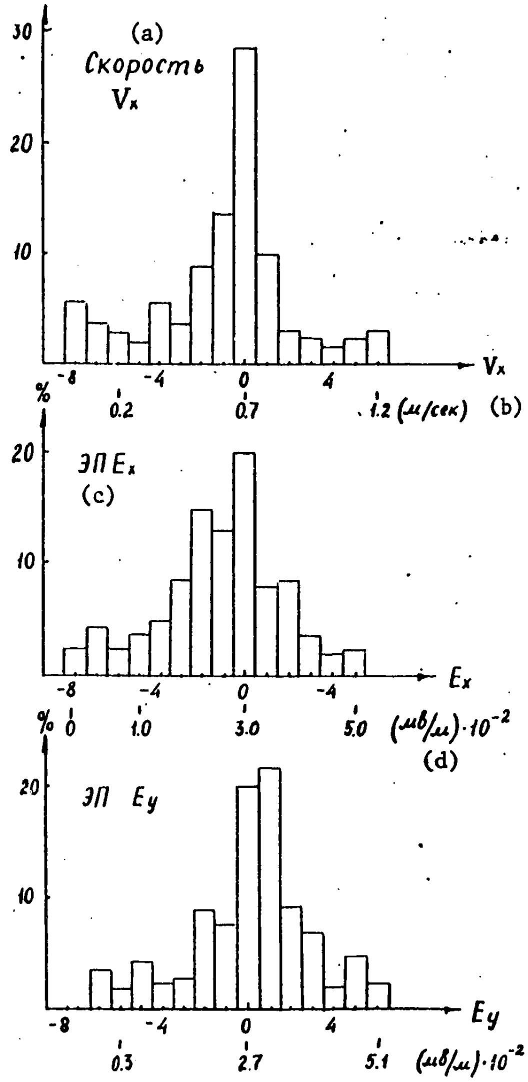

Figure 5.

Key: a. velocity c. electric field E_x
b. m/sec d. (millivolts/meter)$\cdot 10^{-2}$

by the fact that the magnetic field as an integral characteristic is the sum of the interaction of the electric currents in some part of space.

Let us consider the distribution characteristics of the elements of the investigated fields for different sea depths. It is known that in deep water ($H > \lambda/2$) and shallow water ($H < \lambda/2$) waves are characterized by different types of amplitude distribution.

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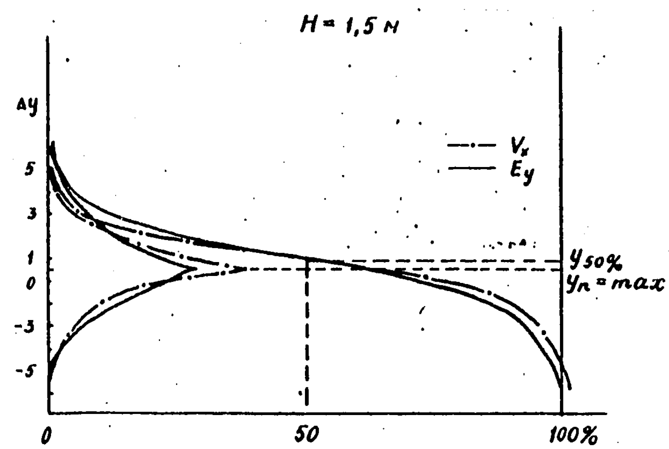

Figure 6.

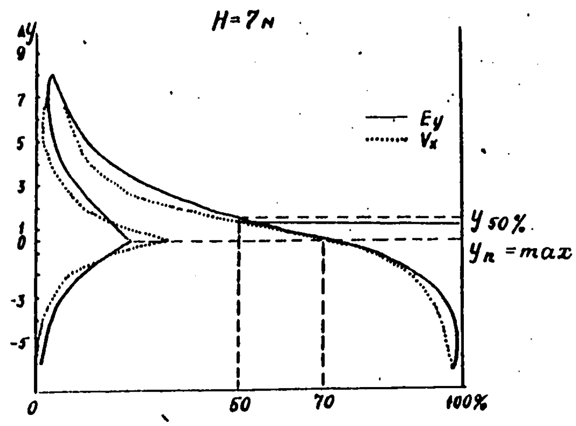

Figure 7.

Thus, a symmetric gaussian curve describes the wave height distribution in shallow water, and the asymmetric Rayleigh distribution curve is characteristic of deep sea distribution.

The results obtained by the experimental data confirm this proposition. For H = 7 meters the wave height distribution curves are asymmetric; some asymmetry is observed also in the velocity distribution ($y \neq y_{max} \neq y_{50\%}$). See Figure 7. The recurrence and guarantee curves of the electric field amplitudes coincide with an accuracy to 5–10% with the corresponding wave height and velocity curves. This case, judging by the element distribution, is an approximation to the "deep" sea model, although, strictly speaking, at a depth of 7 meters the sea can not be considered "deep" ($H > \lambda/2$) for all spectral components.

The statistical wave height distribution in shallow water (H = 1.5 meters), as Figure 6 shows, is characterized by a decrease in the variety of ~~the~~ wave heights as well as the amplitudes of the induced electric field. This is explained by the

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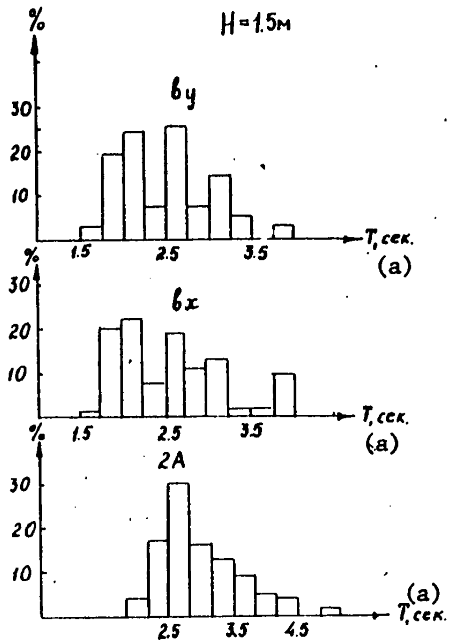

Figure 8.

Key: a. T, sec

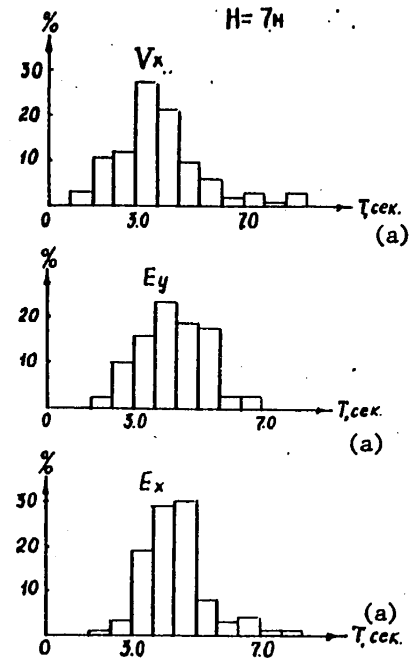

Figure 9.

Key: a. T, sec

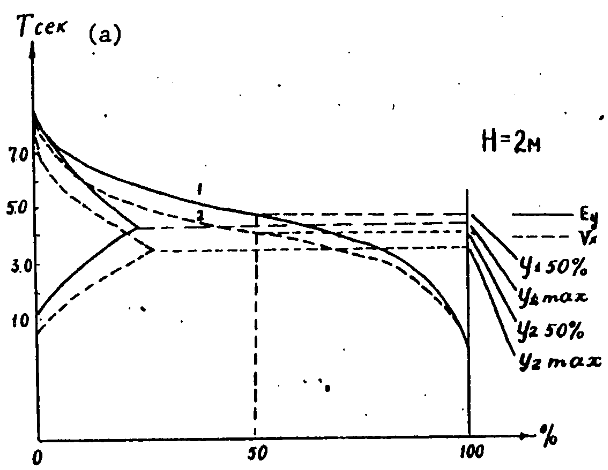

Figure 10.

Key: a. T, sec

breaking of high waves when traveling through shallow water. The amplitude distribution and guarantee curves become symmetric, approaching normal gaussian distribution. Analogous distribution characteristics are manifested by components E_x and E_y of the electric field.

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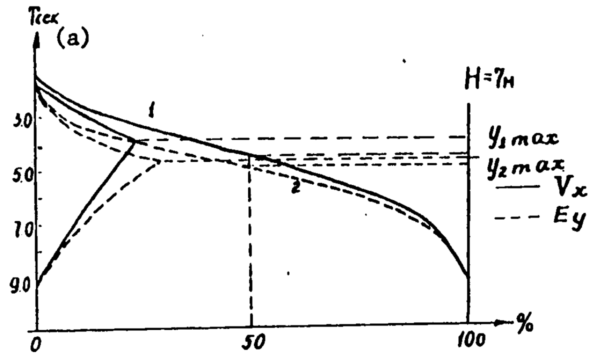

Figure 11.

Key: a. T, sec

Thus, the investigated distribution characteristics make it possible to consider that there is a defined statistical-probability relation with respect to amplitude and period between the parameters of the hydrodynamic source and the components of the induced electromagnetic field. The recurrence and guarantee curves of the electric field and velocity are closest to each other.

This result indicates expediency of the search for a functional relation in the electric fields and velocities during further studies of the magnetohydrodynamic processes in the sea.

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COMPARISON OF TWO TYPES OF DEVICES FOR MARINE ELECTROMAGNETIC SOUNDING

[L. B. Volkomirskaya, G. A. Fonarev, pp 41-45]

The most urgent problem for interpretation of electromagnetic soundings using natural fields is the problem of the influence of the horizontal geoelectric nonuniformities. When performing magnetotelluric soundings in the sea, the effect of the nonuniformities can be especially perceptible, for the measuring devices can be in direct proximity to these nonuniformities. In the theory of marine magnetotelluric soundings, the Tikhonov-Kan'yar bottom unit and separate magnetic device are considered prospective [1].

In this paper a comparison is made between these two types of magnetotelluric devices.

Let us consider the two-dimensional model of nonuniformity. Let a plate of finite thickness d consist of two halfplates in contact along the interface for x = 0 and having conductivities $\sigma_1 \neq \sigma_2$. At the top and bottom of the plate is an insulating medium. The external inducing field is uniform and equal to B_0. Let us propose that at a depth of $d_1 > d$ there is a uniform field source $B = f(B_0, d_1)$. In this case in [2] a method was proposed for gradual approximation to construct the approximate solution. According to this method for the m + 1 approximation the field components are expressed as follows:

$$B_z^{m+1}(y,z) = -\int_{-\infty}^{\infty} B_y^m(y_0,0)\frac{\partial \Gamma_k(\bar{\tau}/y_0,0)}{\partial y}\,dy_0 - \int_{-\infty}^{\infty} B_y^m(y_0,d)\frac{\partial \Gamma_k(\bar{\tau}/y_0,0)}{\partial y}\,dy_0; \quad (1)$$

$$B_y^{m+1}(y,0) = 2B_{0y}(y,0) + \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{B_z^{m+1}(y_0,0)}{y_0-y}\,dy_0; \quad (2)$$

$$B_y^{m+1}(y,d) = 2B_{0y}(y,d) - \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{B_z^{m+1}(y_0,d)}{y_0-y}\,dy_0, \quad (3)$$

where $\Gamma_k(\tau/\tau_0)$ is the Green function. Then for the first approximation considering the expressions for the Green functions given in [3], from (1, 2, 3) it is possible to obtain:

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$$B_z'(r) = -\frac{4}{d}[B_0 + f(B_0, d_1)\sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}(\alpha_{n_1}^{-1} - \alpha_{n_2}^{-1})e^{-\alpha_{n_2}y}\cos\xi_n z; y>0; \quad (4)$$

$$E_x^1(r) = -\frac{4i\omega}{d}[B_0 + f(B_0, d_1)\sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}\cos\xi_n z \times \alpha_{n2}^{-2}[\alpha_{n2}(\alpha_{n1}^{-1} - \alpha_{n2}^{-1})\exp(-\alpha_{n2}y) - 1]; \quad (5)$$

$$B_y'(y,0) = 2B_0 + \frac{4}{\pi d}[B_0 + \sum_{n=0}^{\infty}(-1)^n f(B_0, d)]\sum_{n=0}^{\infty}\varepsilon_n^{-1} \times (\alpha_{n1}^{-1} - \alpha_{n2}^{-1})\{E_i(\alpha_{n2}y)e^{-\alpha_{n2}y} - E_i(-\alpha_{n1}y)e^{\alpha_{n1}y}\}; \quad (6)$$

$$B_y'(y,d) = 2f(B_0, d_1) - \frac{4}{\pi d}[B_0 + \sum_{n=0}^{\infty}(-1)^n f(B_0, d_1)]\sum_{n=0}^{\infty}\varepsilon_n^{-1} \times (\alpha_{n1}^{-1} - \alpha_{n2}^{-1})\{Ei(\alpha_{n2}y)e^{-\alpha_{n2}y} - E_i(\alpha_{n1}y)e^{\alpha_{n1}y}\}. \quad (7)$$

Here

$$\alpha_{nj} = \xi_n^2 - k_j; \quad \varepsilon_n = \begin{cases} 2 & n=0 \\ 1 & n \neq 0 \end{cases} \quad k_j = \frac{1-i}{\sqrt{2}}\sqrt{\omega\mu_0\sigma}$$
$$\xi_n = n\pi/d; \quad j = 1, 2, \ldots;$$

Let us consider the case where $B_{0y}(y,d) = B_{0y}^0(y,0)$ and let us write the relations of the components $E_x/B_y|_{z=d}$ and $B_y|_{z=0}/B_y|_{z=d}$,

$$\left.\frac{E_x}{B_y}\right|_{z=d} = \frac{-\frac{4i\omega}{d}[1+\sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}(-1)^n\{[\frac{\alpha_{n2}}{\alpha_{n1}} - 1]e^{-\alpha_{n2}y} - 1\}\alpha_{n2}^{-2}}{2 - \frac{4}{\pi d}[1+\sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}(\frac{1}{\alpha_{n1}} - \frac{1}{\alpha_{n2}})A}, \quad (8)$$

where:

$$A = E_i(\alpha_{n2}y)e^{-\alpha_{n2}y} - E_i(-\alpha_{n1}y)e^{\alpha_{n1}y};$$

$$\frac{B_y|_{z=0}}{B_y|_{z=d}} = \frac{2 + \frac{4}{\pi d}[1 + \sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}[(\frac{1}{\alpha_{n1}} - \frac{1}{\alpha_{n2}})A]}{2 - \frac{4}{\pi d}[1 + \sum_{n=0}^{\infty}(-1)^n]\sum_{n=0}^{\infty}\varepsilon_n^{-1}[(\frac{1}{\alpha_{n1}} - \frac{1}{\alpha_{n2}})A]} \quad (9)$$

The most general method of interpreting the magnetotelluric soundings in all cases consists in direct calculation and subsequent interpretation of the curve ρ_T, the apparent resistance.

In the case of measuring by the Tikhonov-Kan'yar bottom device the curve ρ_T is calculated by the formula:

$$\rho_T = |Z_n|^2 2T, \quad (10)$$

where $|Z_n| = \left|-\frac{E_x}{B_y}\right|_{z=d}$

The methods of calculating the curve ρ_T for a gradient magnetic sounding are investigated in [4]. We shall use the formula:

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$$\rho_T = \rho_1 \frac{[Re(\frac{B_y(0)}{B_y(d)} ch\,\varkappa d - 1)]^2 + [I_m(\frac{B_y(0)}{B_y(d)} ch\,\varkappa d]^2}{|th\,\varkappa d|^2}, \qquad (11)$$

where $\varkappa = \frac{1-i}{\sqrt{2}}\sqrt{\omega\mu_0\sigma}$.

For our case -- a thick plate -- this formula has a small error. Let us convert formula (11). For this purpose we make the assumption that $d \gg 1/Re\,\varkappa$.

Then:

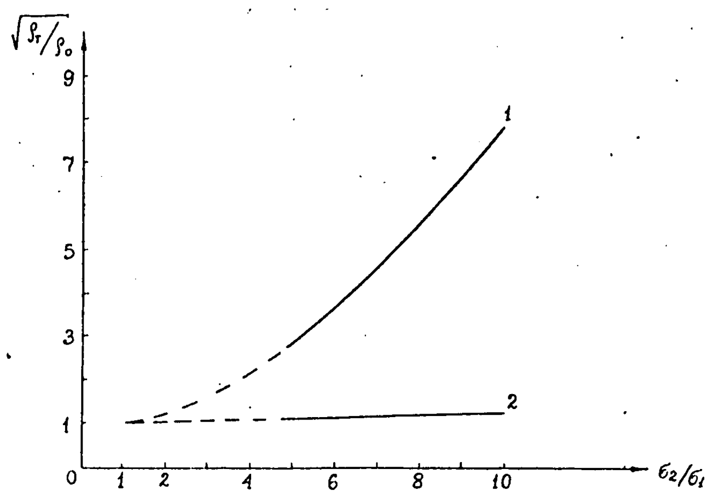
$$\rho_T = \rho_1 \left(\left|\frac{B_y(0)}{B_y(d)}\right|\right)^2 \left(th^2 x + \frac{1}{2}\right),$$

where $x = d\sqrt{\omega\mu\sigma/2}$.

It is theoretically possible also to perform more exact calculations by formula (11), but in this case it is necessary to perform the calculations on high speed computers.

In the figure there is a graph of the functions $\sqrt{\rho_T/\rho_0}$ for different relations between the conductivities of two halfplates, where we denote the apparent resistance of a uniform plate as ρ_0.

For the calculations of $E_x/\dot{H}_y\big|_{z=d}$ and $\frac{H_y|_{z=d}}{H_y|_{z=0}}$ by formulas (8, 9) we assumed that the measurements are performed in the sea at distances of 0.1d from the nonuniformity. With approach of the observation point to the nonuniformity the relations must be maintained qualitatively. The solid lines join the points calculated by



(8, 9) with limitation to the first term in the series considering smallness of $\alpha_{02}y$, $\alpha_{01}y$; the dotted curves were obtained from the asymptotes of the formulas (8, 9) for $\sigma_1 \simeq \sigma_2$. Curve 1 is constructed for measurements by the Tikhonov-Kan'yar method. Curve 2 is constructed for the method of magnetic gradient sounding.

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A comparison of the two devices permits the conclusion to be drawn that the Tikhonov-Kan'yar bottom device is significantly more strongly subjected to the influence of the nonuniformity. This indicates that the distortions in the electric field are greater than in the magnetic field.

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MEASURING THE SEA WAVE-INDUCED ELECTRIC FIELD

[G. A. Fonarev, V. Yu. Semenov, pp 46-51]

It is known that during propagation of sea waves in the earth's magnetic field not only magnetic, but also electric fields are induced. The calculation of the magnitude of the induced electric field based on the potential hydrodynamic theory of motion of a fluid in a two-dimensional progressive wave, was performed by the authors of [1, 5]. Analogous calculations for waves characterized by the eddy nature of motion of the fluid in them were performed by the authors of reference [2]. Inasmuch as the process of induction of the electric field by sea waves is described most simply by a mathematical model presented in the first papers, the analysis of the measurement procedure and interpretation of the electric field of the waves is performed on the basis of this model.

The electric field induced by sea waves is measured usually by the method of measuring the potential difference between two different points in space inside the fluid. The magnitude of the electric field potential ϕ at any point of a two-dimensional wave is described in the form [1]:

$$\varphi(x_0; z_0) = a(z_0)\cos(kx_0 - \omega t).$$

Here a is the amplitude of the induced potential which depends on the speed of the fluid particles in the wave and on the intensity of the constant magnetic field of the earth; $k = 2\pi/\lambda$, $\omega = 2\pi/T$, where λ is the wavelength, and T is its period. The waves are considered to be steady, propagated in the direction of the X-axis.

Let us consider the case of measuring the horizontal field induced by the wave. Let us propose that the potential difference is measured between two points in the sea lagging behind each other a distance L in the direction of propagation of the wave. The magnitude of the recorded potential difference is then written in the form:

$$\varphi(-L/2; z_0) - \varphi(L/2; z_0) = -2a(z_0)\sin\left(\frac{\pi L}{\lambda}\right)\sin\omega t.$$

The expression for the potential difference, if it is measured in the vertical direction can be written in the form:

$$\varphi(x_0; z_0) - \varphi(x_0; z_0 + L) = [a(z_0) - a(z_0 + L)]\cos(kx_0 - \omega t).$$

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Thus, from the expressions obtained it is obvious that the measurements of the horizontal and vertical electric field of the waves differ noticeably; the potential difference in the vertical direction does not depend on the relation between the wavelength and the distance between the electrodes at the same time as the horizontal field is essentially determined by this ratio.

The measured potential difference of the horizontal electric field as a function of the sea wave length expressed in magnitudes of the length of the measuring base is presented in Figure 1. As the unit in the figure, the maximum possible signal picked up from the electrodes equal to 2a is used. Thus, the measured potential difference can be highly insignificant, or absent in general in the case where the distance between the electrodes is a multiple of an integral number of sea wave lengths.

It is necessary to note that the indicated procedural characteristic of measuring the potential difference can in individual cases lead to the appearance of a horizontal electric field of groups of waves on the recordings. This situation can be realized when the spacing between the electrodes is equal to or a multiple of the basic wavelength in the sea wave spectrum. For example, when measuring a horizontal electric field in the sea with a depth of three meters waves with periods of 3.8 and 4.8 seconds will be recorded with maximum possible amplitudes if the spacing between the electrodes is 60 meters inasmuch as the lengths of these waves are equal to 17 and 24 meters respectively [3]. The periods of these waves are close and, consequently, the formation of beats on the electric field recording is possible. Thus, the groups of waves isolated by the recording of the horizontal electric field can be unrelated to the group structure of the wind-driven wave field in the sea [4]. It is possible to identify the groups of oscillations in the recording of the electric field with the groups of the wind-driven sea waves directly only when observing the vertical component of this field.

Let us now consider the procedure for interpreting the data carried out most frequently with the application of spectral analysis. From the above-investigated procedure for measuring the electric field induced by sea waves it follows that in the spectrum of the potential difference in the horizontal direction sharp decreases in magnitude of the spectral density are observed on frequencies which correspond to wave lengths which are multiples of the length of the measuring base. Therefore when interpreting the estimates of the spectral density of the process which is a recording of the potential difference of the horizontal electric field of the sea, it is necessary to consider that the usually applied smoothing of the spectral density can lead to significant reduction of the signal in the frequency range, the wave lengths of which are less than the length of the measuring base.

Now let us consider the experimental data. In Figure 2 spectra are presented for the synchronously recorded amplitudes of the sea wave and variations of the horizontal electric field. As is obvious from the figure, the spectra of the investigated processes differ noticeably: on the spectrum of the electric field recorded in the direction perpendicular to the direction of wave propagation with a distance between the electrodes of 300 meters, sharp, statistically significant "troughs" in the spectral density are obvious at the same time as analogous phenomena are not observed in the wave spectrum. Thus, it is possible to propose that waves with periods of about 10 and 20 seconds have a crest length equal to or a multiple of 300 meters.

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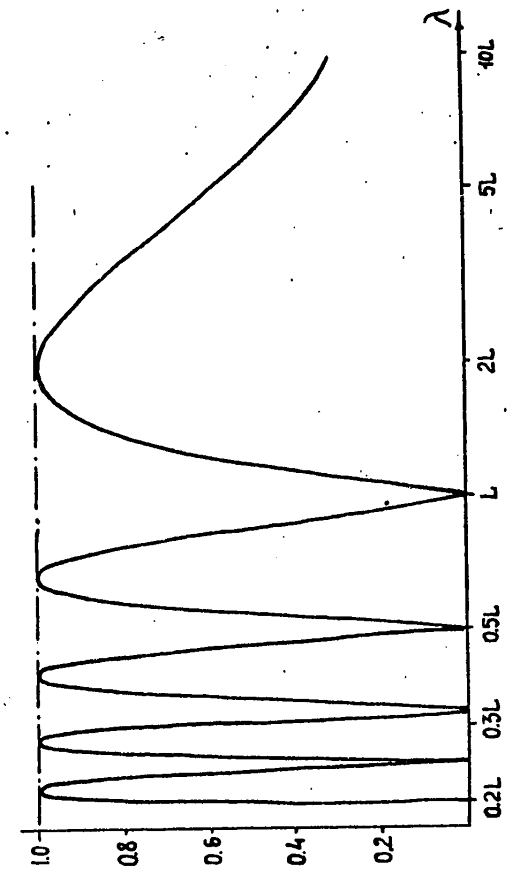

Figure 1.

Thus, using the peculiarities of the procedure for observing the horizontal electric field induced by the sea waves, it is possible to determine the relation between the wavelength and the length of its crest and also directly to check the hydrodynamic disperse relation using a spectral analysis of the recordings of this field.

The conclusions drawn are valid both for stationary measuring bases and in the case of moving electrodes. However, in the last case it is necessary to consider that the recorded period of the electric field oscillations can fail to compare with the sea wave period.

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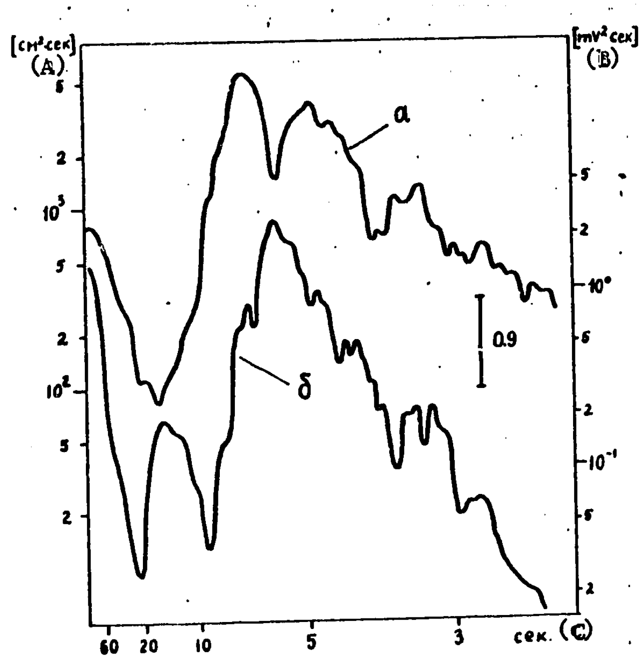

Figure 2.

Key: A. cm^2-sec
B. mv^2-sec
C. sec

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ESTIMATING ELECTRIC FIELDS CREATED BY A TWO-DIMENSIONAL WAVE SPECTRUM

[M. M. Bogorodskiy, pp 52-61]

Hydrophysical electrical electrode studies are performed for the solution of a number of scientific and practical problems. In this paper a study is made of the possibilities of interpreting the data from the point of view of the theory of small-amplitude potential waves, beginning with the concepts of sea waves as the probable process having the property of ergodicity. In the linear approximation the surface can be represented in the form of the sum of a large number of simple waves having different amplitudes, lengths, propagation directions and random phases [1, 3, 4]. The results are found in the form of integral spectra.

Let us introduce the cartesian coordinate system xoy, placing the origin of the coordinates on the level of the undisturbed sea surface. The elementary wave, the beam of which makes an angle θ with the x-axis can be written in the form

$$\xi(x,y,z,t) = a\frac{\operatorname{sh} k(z+h)}{\operatorname{sh} kh}\cos[\omega t+\varepsilon-k(x\cos\theta+y\sin\theta)], \quad (1)$$

where $\xi(x, y, z, t)$ is the vertical deviation,

$k = 2\pi/\lambda$ is the wave number (λ is the wave length),

$\omega = 2\pi/T$ is the angular frequency (T is the wave period),

h is the depth of the sea,

ε is an arbitrary phase shift.

Let us first define the electric potential caused in the water by the effect of the earth's magnetic field H_x, H_y, H with monochrome (1). The results of studying the electric field of a monochromatic wave [6] permits recording the electric potential for such a wave in the form:

$$\varphi(x,y,z,t) = C\cdot[H_y\cos\theta - H_x\sin\theta]\cdot\xi(x,y,z,t), \quad (2)$$

where H_x and H_y are the components of the earth's magnetic field,

$C = \frac{\lambda}{T} = \sqrt{\frac{g}{k}\operatorname{th} kh}$ is the phase velocity.

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The wave elevations will be represented in the form of the sum of the large number of monochromes of the type of (1), describing each of them in the form:

$$\xi_{ij}(x,y,z,t) = a(\omega_i \theta_j)\sqrt{\Delta\omega\Delta\theta} \cdot \frac{sh\, k_i(z+h)}{sh\, k_i h} \times \cos[\omega_i t + \varepsilon_{ij} - k_i(x\cos\theta_j + y\sin\theta_j)]. \quad (3)$$

In this case the total wave elevation can be represented in the form:

$$X(x,y,z,t) = \sum_{i=-m}^{m}\sum_{j=-n}^{n} a(\omega_i \theta_j)\sqrt{\Delta\omega\Delta\theta} \cdot \frac{sh\, k_i(z+h)}{sh\, k_i h} \times \cos[\omega_i t + \varepsilon_{ij} - k_i(x\cos\theta_j + y\sin\theta_j)]. \quad (4)$$

Here, in accordance with the papers by Yu. M, Krylov [1] and V. Pierson [4] we shall consider that the phase ε_{ij} of each term of (3) is a random variable uniformly distributed in the interval from 0 to 2π, on the basis of which the value of X (x, y, z, t) is also random. We shall also consider that the phase ε_{ij} is an aligned ergodic function of the horizontal coordinates and time so that for the point A (x_1, y_1, z_1):

$$\varepsilon_{ij} = \varepsilon_{ij}(x_1 y_1 t), \quad (5)$$

and also

$$\frac{\partial}{\partial z}\varepsilon_{ij} = 0. \quad (6)$$

The total electric potential of the point A with respect to the bottom where it is found to be equal to zero will be found by summing the elementary terms of (2):

$$\Phi(x,y,z,t) = \sum_{i=-m}^{m}\sum_{j=-n}^{n} \Psi_{ij}(\omega,\theta,z) \cdot \xi_{ij}(x,y,\theta,t), \quad (7)$$

where for multiplicity of the recording the following function is introduced:

$$\Psi_{ij}(\omega,\theta,z) = C_i[H_y\cos\theta_j - H_x\sin\theta_j]\frac{sh\, k_i(z+h)}{sh\, k_i h} \quad (8)$$

or, what amounts to the same thing:

$$\Psi_{ij}^2(k,\theta,z) = \frac{g}{k}\, th\, k_i h[H_y\cos\theta_j - H_x\sin\theta_j]^2\left[\frac{sh\, k_i(z+h)}{sh\, k_i h}\right]^2. \quad (9)$$

The electric potential dispersion of the point (x, y, z, t) can now be written as the sum of the individual contributions of the type:

$$\Delta_{ij}\overline{\Phi^2} = \frac{1}{2}a^2(\omega_i\theta_j)\Delta\omega\,\Delta\theta \cdot \Psi_{ij}^2. \quad (10)$$

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On transition to continuity, the integral spectrum of the electric potential of the point acquires the form:

$$\overline{\Phi^2}(z) = \frac{1}{2}\int_0^\infty\int_{-\pi}^{\pi} \Psi^2(\omega,\theta,z)\, a^2(\omega,\theta)\, d\theta\, d\omega. \tag{11}$$

The intensity of the electric field E(x, y, z, t) can also be considered as the sum of the intensities created by the individual monochromes. From (7) we have:

$$E_z(x,y,z,t) = \frac{\partial \Phi(x,y,z,t)}{\partial z} = \sum_{i=-m}^{m}\sum_{j=-n}^{n} k_i \,\mathrm{cth}(z+h)\, \Psi_{ij}(z)\, a(\omega_i\theta_j)\sqrt{\Delta\omega\Delta\theta} \times \cos[\omega_i t + \varepsilon_{ij} - k_i(x\cos\theta_j + y\sin\theta_j)]; \tag{12}$$

$$E_x(x,y,z,t) = \frac{\partial \Phi(x,y,z,t)}{\partial x} = \sum_{i=-m}^{m}\sum_{j=-n}^{n} k_i \Psi_{ij}(z)\, a(\omega_i\theta_j)\sqrt{\Delta\omega\Delta\theta}\,\cos\theta_j \times \sin[\omega_i t + \varepsilon_{ij} - k_i(x\cos\theta_j + y\sin\theta_j)]; \tag{13}$$

$$E_y(x,y,z,t) = \frac{\partial \Phi(x,y,z,t)}{\partial y} = \sum_{i=-m}^{m}\sum_{j=-n}^{n} k_i \Psi_{ij}(z)\, a(\omega_i\theta_j)\sqrt{\Delta\omega\Delta\theta}\,\sin\theta_j \times \sin[\omega_i t + \varepsilon_{ij} - k_i(x\cos\theta_j + y\sin\theta_j)]. \tag{14}$$

When making the transition to the continuity the integral spectrum of the components of the electric field intensity at the point acquires the form:

$$\overline{E_z^2}(z) = \frac{1}{2}\int_0^\infty\int_{-\pi}^{\pi} k^2(\omega)\,\mathrm{cth}^2(z+h)\,\Psi^2(\omega,\theta,z)\, a^2(\omega,\theta)\, d\theta\, d\omega; \tag{15}$$

$$\overline{E_x^2}(z) = \frac{1}{2}\int_0^\infty\int_{-\pi}^{\pi} k^2(\omega)\cos^2\theta\,\Psi^2(\omega,\theta,z)\, a^2(\omega,\theta)\, d\theta\, d\omega; \tag{16}$$

$$\overline{E_y^2}(z) = \frac{1}{2}\int_0^\infty\int_{-\pi}^{\pi} k^2(\omega)\sin^2\theta\,\Psi^2(\omega,\theta,z)\, a^2(\omega,\theta)\, d\theta\, d\omega, \tag{17}$$

where $\psi^2(\omega, \theta, z)$ can be represented by expression (9) considering that $k(\omega)$ is the solution of the equation:

$$\frac{\omega^2}{g} = k\, th\, kh. \tag{18}$$

It is essential to note that for z > -h even a narrow region of angles θ for which $a^2(\omega, \theta) \neq 0$ makes a defined contribution to the spectra of all three components of the electric field vector. From formulas (12), (14) and (15) it is obvious that E_z does not have correlation with E_x or E_y. Simultaneously it is obvious that the the two-dimensional terms E_{ijx} and E_{ijy} are distinguished only by the proportionality factor which permits confirmation of the presence of the correlation between any mutually perpendicular components of the horizontal intensity of the electric field at the point with the exception of the isolated directions in which the correlation changes sign.

In the following calculations we shall consider that the two-dimensional energy spectrum of the electric potential $b^2(u, v, z)$ is given as a function cf the wave numbers u and v directed along the x and y axes, respectively. The variables u and v will be introduced in terms of the variables ω and θ as follows:

$$\left.\begin{aligned} u &= k(\omega)\cos\theta \\ v &= k(\omega)\sin\theta \end{aligned}\right\} \tag{19}$$

where k(ω) is the solution of equation (18).

In the new variables the expression for the integral spectrum of the electric potential will be written in the form:

$$\overline{\Phi}^2(z) = \frac{1}{2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} b^2(u, v, z)\, du \cdot dv. \tag{20}$$

In particular, the spectrum $b^2(u, v, z)$ can be given in the form:

$$b^2(u, v, z) = \frac{a^2(\omega, \theta)\,\Psi^2(\omega, \theta, z)}{k(\omega)\,\frac{\partial k(\omega)}{\partial \omega}}, \tag{21}$$

where the inverse transition from the wave numbers (u, v) to the variables (ω, θ) is easily realizable considering (18):

$$a^2(\omega, \theta)\,\Psi^2(\omega, \theta, z) = b^2[u(\omega, \theta); v(\omega, \theta), z] \times k(\omega) \cdot \frac{\partial k(\omega)}{\partial \omega}, \tag{22}$$

however, further conclusions do not explicitly depend on the form of expression (20).

Let us consider the potential difference U_{AB} between the points A(x, y, z) and B(x_2, y_2, z). Let us mentally connect the points A and B by a straight line making the angle $\hat{\theta}$ with the X-axis and let us consider, according to the monograph by Yu. M. Krylov [1], the course of the potential along this line at some fixed point in time. The potential spectrum along the line AB $\bar{C}^2_{\hat{\theta}}(u' z)$, expressed in terms of the wave number u' taken along the ray:

$$\hat{\theta} = \operatorname{arctg} \frac{x_2 - x_1}{y_2 - y_1}, \tag{23}$$

emerging from the origin of the coordinates of the initial spectrum $b^2(u, v, z)$ has the form:

$$\frac{1}{2} C_{\hat{\theta}}^2(u', z) = \frac{1}{2} \int_{-\infty}^{\infty} b^2(u, v, z)\, dv', \tag{24}$$

where

$$\left.\begin{aligned} u' &= u \cos\hat{\theta} + v \sin\hat{\theta} \\ v' &= -u \sin\hat{\theta} + v \cos\hat{\theta} \end{aligned}\right\} \tag{25}$$

Inasmuch as the spectrum (24) and the autocorrelation function for the potential $\mathcal{K}_{\hat{\theta}}(R, z)$ with respect to the same direction are uniquely related [5], we have:

$$\mathcal{K}_{\hat{\theta}}(R, z) = \frac{1}{\pi} \int_0^{\infty} \frac{1}{2} C_{\hat{\theta}}^2(u', z) \cos Ru'\, du'. \tag{26}$$

Now we can write the dispersion of the potential difference at the points A and B in terms of the known values of

$$\overline{U^2}(R, \hat{\theta}, z) = \overline{(\Phi_A - \Phi_B)^2} = 2\left[\overline{\Phi^2}(z) - \mathcal{K}_{\hat{\theta}}(R, z)\right] \tag{27}$$

where

$$R = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{28}$$

$\Phi^2(z)$ is the dispersion of the aligned function $\Phi(z)$, for example, (11), (20).

The magnitude of the autocorrelation function of the electric potential with respect to direction entering into expression (27) can be represented in the form of the integral frequency spectrum if we consider that from (26), (25), (24), (20) and (19) it follows that:

$$\frac{\partial \mathcal{K}_{\hat{\theta}}(R, z)}{\partial k} = \int_{-\pi}^{\pi} \frac{1}{2} b^2[k \cos\theta; k \sin\theta, z] \cos[Rk \cos(\theta - \hat{\theta})]\, d\theta, \tag{29}$$

from which considering (18) we have:

$$\mathcal{K}_{\hat{\theta}}(R, z) = \int_0^{\infty} æ_{\hat{\theta}}[R, z, k(\omega)]\, d\omega, \tag{30}$$

where

$$æ_{\hat{\theta}}[R, z, k(\omega)] = \frac{2}{\sqrt{g}} \frac{\sqrt{k \cdot \operatorname{th} kh}}{\left(\operatorname{th} kh + \frac{h}{\operatorname{ch}^2 kh}\right)} \times$$

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$$\times \int_{-\pi}^{\pi} \frac{1}{2} B^2 [k\cos\theta; k\sin\theta, z] \cos[Rk\cos(\theta-\hat{\theta})] d\theta;$$

$$\omega = \sqrt{gk \, th \, kh};$$

$$d\omega = \frac{\sqrt{g}}{2} \frac{(th\,kh + \frac{h}{ch^2 kh})}{\sqrt{k\,th\,kh}}.$$

In the case where the spacing between the electrodes is large, that is, for

$$R \gg \bar{\lambda}, \bar{L} \qquad \mathcal{K}_{\hat{\theta}}(R, z) \to 0, \tag{31}$$

where $\bar{L}$ is the average crest length expression (27) degenerates, acquiring the form:

$$\overline{\Phi^2}(z) = \frac{1}{2} \overline{U^2}(z). \tag{32}$$

In the special case where the wave spectrum is limited to a comparatively narrow frequency band $\Delta\omega$ and the directions $\Delta\theta$ (swell), applying the theorem of the mean to the expressions (11), (16) and (17) and assuming, without limiting the generality $\hat{\theta} = 0$, considering (32) we have:

$$\overline{E_x^2} \simeq k^2(\bar{\omega}) \overline{\Phi^2}(z) = \frac{1}{2} k^2(\bar{\omega}) \overline{U^2}(z); \tag{33}$$

$$\overline{E_y^2} \simeq 0. \tag{34}$$

The course of the horizontal electric field intensity E_x in the vicinity of the point (x, y, z, t) can now be approximated in the form:

$$E_x(x, y, z, t) = \frac{1}{\sqrt{2}} k(\bar{\omega}) \sqrt{\overline{U^2}(z)} \sin[\bar{\omega}t - k(\bar{\omega}) + \bar{\varepsilon}]. \tag{13}$$

Sometimes instead of the mean square values for the speed of the estimates it is convenient to use the mean modulus values. As a result of the proposition of narrowness of the frequency band we have:

$$\sqrt{\overline{U^2}(z)} \simeq \frac{\pi}{2\sqrt{2}} \overline{|U(z)|}$$

and it is possible to rewrite (13) in the form:

$$E_x(x, y, z, t) \simeq \frac{\pi}{4} k(\bar{\omega}) \overline{|U(z)|} \sin[\bar{\omega}t - k(\bar{\omega})x + \bar{\varepsilon}]. \tag{13}$$

Expressing $k(\bar{\omega})$ in terms of the average wavelength $\bar{\lambda}$, we have the working formula for estimating the mean amplitude of the horizontal component of the electric field $\overline{am}(E_x)$ at a depth z for the swell propagated from the direction coinciding with the X-axis:

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$$\overline{am}\left[E_x(z)\right] \simeq \frac{4.44}{\lambda}\sqrt{\overline{U^2(z)}} \simeq \frac{4.93}{\lambda}\overline{|U(z)|}. \qquad (35)$$

Considering (13), (13) and (31), we have:

$$\overline{am}\left[\Phi(z)\right] \simeq \frac{\pi}{4}\overline{|U(z)|} \simeq \frac{1}{\sqrt{2}}\sqrt{\overline{U^2(z)}}, \qquad (36)$$

where the sign $\overline{am}$ denotes the average amplitude. Let us note that the expressions (35) and (36) do not depend on the form (10) of the function $\psi^2(\omega, \theta, z)$ or on the proposition (6) which require [2] confirmation. Significant generality of the expressions (35) and (36) makes it possible to use them for experimental checking of the relations (6) and (10).

Conclusions:

1. Within the framework of the linear theory of small-amplitude waves propagated in a sea of arbitrary fixed depth and interacting with the earth's magnetic field, two-dimensional integral spectra are obtained for the electric potential and three components of the electric field at the point where the two-dimensional spectrum of the wave elevations on the sea surface is given. It is demonstrated that for all horizons above the bottom, even the narrow nonzero region of the two-dimensional wave spectrum creates nonzero spectra of all three components of the electric intensity field; here the correlation between the vertical and horizontal components of the electric intensity within the framework of the linear model is absent, and the horizontal components of the electric intensity, in general, are correlated.

2. In the general case of a two-dimensional spectrum of the electric potential connected with the two-dimensional wave spectrum, the expression is found for the integral spectrum of the electric potential difference arising at the ends of an arbitrarily oriented horizontal base as a function of its length and orientation. It is demonstrated that if the length of the base is much greater than the mean wave length (or the mean crest length), and the spectrum of the electric potential difference at its ends will be equal to twice the spectrum of the electric potential of the point located at the same depth, and it does not depend on the length and direction of the base. The relation found from its experimental study of the variation with depth of the electric potential spectrum, independently of the propositions regarding the distribution of the phase shifts and the damping with depth and also independently of the presence of a "zero" point for electric measurements.

3. In the special case of limiting the two-dimensional wave spectrum by the narrow frequency band and propagation angles (swell), operating relations have been obtained for finding the mean amplitude values of the electric potential and horizontal component of the electric intensity at the point where, for example, by the measurement results the magnitude of the mean square (or the mean modulus) value of the aligned potential difference on a "long" base and the mean wave length are known. These relations also do not depend on the propositions of the course of the electric potential field with depth.

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GENERAL PROPERTIES OF THE ANOMALOUS MAGNETIC FIELD IN THE WORLD OCEAN

[V. G. Larkin, V. N. Lugovenko, A. G. Popov, pp 62-79]

In accordance with the work program of the Soviet Antarctic Expeditions from 1970 to 1974 on the expeditionary vessels, diesel electric "Ob'," diesel electric "Navarin" and scientific research vessel "Professor Vize," measurements were made along the way of the modulus of the total intensity of the earth's magnetic field.

The surveys were made along the longest routes, which were in the Atlantic and Anarctic Oceans (Figure 1). The total length of the processed marine magnetic profiles is about 100,000 km.

Magnetic observations were performed by the co-workers of the IZMIRAN Institute using the towed marine quantum T-magnetometer providing for obtaining field values with accuracy to ± 2 gamma. The mean square error of the surveys, including the errors for field variation, inaccuracy in gridding the vessel, and deviation amounted to about ± 35 gammas.

All the data obtained on the sparse profile grid permit the solution of the most general problems with respect to interpretation of the anomalous magnetic field and its relations to the geological structure of the ocean floor.

At the present time throughout the entire world interest is increasing in the exploitation of the mineral resources of the world ocean at greater and greater depths and at greater and greater distance from the shore.

The revelation of the history of the world ocean, its tectonic regionalization are important theoretical problems, the solution of which is necessary, in particular, also to discovery of the laws of the location of mineral deposits [1].

Magnetometry is perhaps the only geophysical method which can provide information not only about the structure of our planet, but also about the evolution of its development. The geophysical analysis of the anomalous magnetic field in the oceans is an effective means of determining the chronological, kinematic and geometric characteristics of movement of the lithospheric plates.

Since the results of the hydromagnetic survey are a continuous recording of the geomagnetic field along individual profiles of great extent, it is expedient to subject the anomalous magnetic field along these profiles to a statistical analysis. The expediency of a statistical analysis is connected with the fact that it permits

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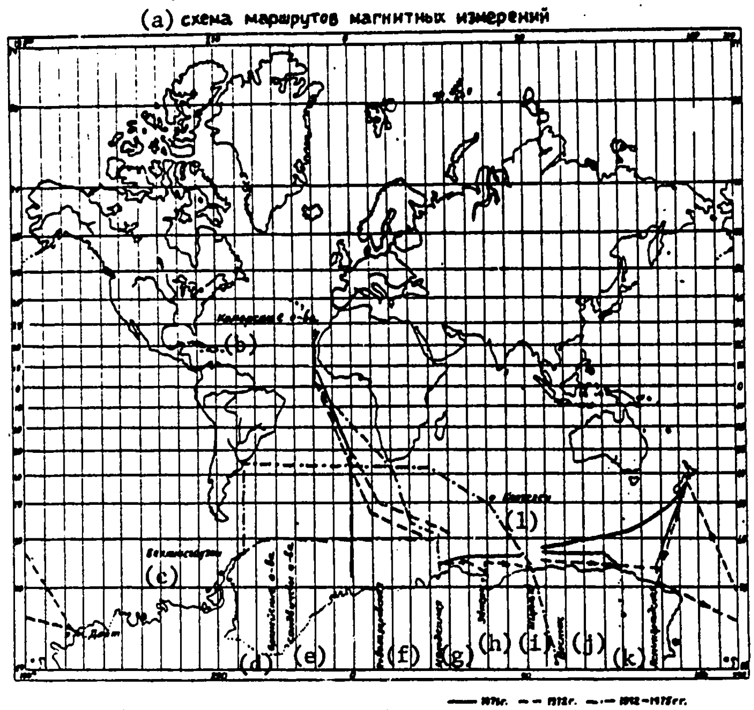

Figure 1.

Key: a. chart of the magnetic measurement routes
b. Canary Islands
c. Bellingshausen Iles
d. Orkney Islands
e. Sandwich Islands
f. Novolazarevskaya station
g. Molodezhnaya
h. Amery
i. Mirnyy
j. Vostok
k. Leningradskaya
l. Kerguelen

discovery of the principal defining properties of the field which can be related to the basic peculiarities of the structure of the ocean floor. In contrast to the usually accepted procedure when individual anomalies are interpreted, in a statistical analysis preliminary separation of the field as a united process into its individual elements takes place, each of which reflects some property of the anomalous magnetic field which, in turn, is related to some peculiarity of the structure of the ocean crust.

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Let us present a brief description of the investigated statistical parameters and their physical meaning.

The dispersion of the anomalous magnetic field R_0 basically represents the characteristic of magnetization of the magnetic sources (as a rule, basalts making up the sea bed).

The correlation radius of the anomalous magnetic field $r_{0.3}$ reflects the horizontal dimensions of the anomalies, which is basically connected with the depth of the sources and their horizontal dimensions.

The mathematical expectation of the anomalous magnetic field (M) represents the total effect: inaccuracy of approximation of the normal field, average depth of sources, measure of magnetization, and so on.

For estimation of the general properties of the field and its relation to the geological structure of the earth's crust, a statistical analysis has been used more than once. Thus, in reference [2] a correlation analysis of the anomalous magnetic field of the Pacific Ocean was performed, and the difference in values of $r_{0.3}$ and R was noted for the mid-ocean rise and slopes. Tectonic mapping was carried out basically with respect to the general pattern of distribution of the anomalous magnetic field (the amplitude of the anomalies, their horizontal dimensions) using data on the statistical characteristics of the anomalous magnetic field (the dispersion and correlation radius). In reference [3] a statistical analysis is presented of the circular latitudinal profile of the vertical component of the magnetic field passing near 40° south latitude, and the possibility of applying the autocorrelation analysis for regionalization of the anomalous fields is demonstrated. The statistical characteristics of the anomalous magnetic field in the central part of the Atlantic Ocean were investigated in reference [4] in which the results of the autocorrelation analysis are also presented. In this paper regionalization of the sea bed is carried out with respect to the morphological attributes, and a study is made of the behavior of the statistical parameters within the limits of the isolated zones. In reference [5] a study is made of the properties of the anomalous magnetic field in the vicinity of the Indian Ocean using the sliding energy spectrum procedure. A statistical analysis of the anomalous magnetic field of the Indian Ocean was also carried out in reference [6] in which a method was developed for quantitative discription of the variations of the anomalous magnetic field on long individual profiles.

However, up to now the problem of the difference or similarity in the statistical properties of the anomalous magnetic field of the continental and ocean crust has not been finally solved. Thus, in reference [7] the conclusion is drawn that the structure of the continental crust differs theoretically from the structure of the ocean crust, which finds it reflection in the difference of the statistical properties of the anomalous magnetic field. On the contrary, in reference [8] the authors arrive at the conclusion of similarity of the average characteristics of the magnetic field of the continents and oceans. This difference in points of view obviously is related first with the fact that when analyzing the anomalous magnetic field various procedures were used, and secondly, the fact that in these papers the regionalization of the territory of the dry land and the oceans as uniform regions was not clearly carried out in the sense of the geological structure of the region.

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In references [2, 9] an estimate is made of the statistical properties of the anomalous magnetic field separately for different tectonic provinces and it was demonstrated that the tectonic provinces uniform in the genesis sense have stationary anomalous magnetic fields. For this purpose in order more precisely to define the concept of the nature of the anomalous magnetic field of the ocean crust and its relation to the structure of the sea bed, we made estimates of the statistical properties of the field along a number of profiles of the marine magnetic survey. The statistical analysis procedure was identical to the one used in reference [9] in which basically an analysis of the anomalous magnetic fields of the continents was performed.

The ocean floor can be divided into four large provinces differing with respect to origin and development [4]: the midocean ridges, the slopes of the ridges, the deep sea trenches and coastal regions. Therefore when generalizing the statistical analysis of the anomalous magnetic field, average field characteristics were determined separately for each province.

The procedure for estimating the statistical properties of the field was reduced to the following. The normal field T_H was isolated for all profiles of the surveys by representation of it by a spherical harmonic series with n = 9 harmonics. Then the obtained difference $\Delta T_a = T - T_H$ was centered, and the statistical parameters of the anomalous magnetic field were calculated for the aligned values of the anomalous field.

In order to obtain information on the statistical properties of the anomalous magnetic field along the profiles, a special program was used to perform the calculations on a digital computer. The essence of the program consists in the following:

1) Information is input to the digital computer on the profile of the field T (the coordinates of the points of rotation of the profile, observed values of T every 5 km, the magnitude of the secular variation).

2) For each value of the field T the normal field T_H and the field ΔT_a are calculated.

3) The file of values of ΔT_a formed is aligned for the segment of the profile L which must "slide" along the initial profile. For the aligned values of the anomalous magnetic field, the autocorrelation function and other statistical characteristics are calculated.

4) Then the sliding segment L is shifted along the file of values ΔT_a by some amount ΔL, the calculation is repeated, then a new shift by ΔL takes place, and so on to the end of the profile.

For all routes L was selected equal to 1020 km, and ΔL = 125 km.

The selected model of the normal field is not always sufficiently high quality. As a result of analysis of the mathematical expectation of several sections in the Antarctic Ocean it was discovered that inexact alignment of the anomalous magnetic fields along the profiles is connected with the fact that:

1) the variable part of the field is not considered in the analysis;

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2) the model of the spherical harmonic series approximates the main geomagnetic field in southern latitudes with some error (the mathematical expectation reaches 150 gammas).

By the results of statistical processing of the analyzed profiles of the anomalous magnetic field we constructed maps of the graphs of some of the statistical parameters. In Figures 2 and 3 the maps of the graphs are presented for the parameter σ, ($\sigma = \sqrt{R_0}$) and the correlation radius $r_{0.3}$ of the anomalous field.

The maps were constructed as follows. All of the analyzed sections were applied to the base with a scale of 1:15,000,000, and the profiles of the sliding segments were numbered along the profiles.

The lines for the arrangement of the profiles corresponded to the median value of each of the investigated statistical parameters when constructing the graphs of these parameters along the profiles. The values of the parameters exceeding the median were plotted to the north (for sublatitudinal profiles) or to the east (for submeridianal profiles) of the profile line and they were plotted on the maps by solid lines on the corresponding vertical scale for each of the statistical parameters. The dotted lines designate the values of the parameters which are less than the median value.

When analyzing the maps of the graphs of the statistical parameters it is necessary to consider first of all the requirement of co-dimensionality in which the relation is laid out between the choice of the length of the analyzed section and the size of the tectonic structures. The selected length of the profile 1020 km, which is optimal for statistical representativeness of the analysis can be recognized as commensurate with the large tectonic structures such as the ocean trenches, the slopes of the midocean rises and the seamounts themselves. Secondly, it is necessary to consider the requirement of sameness of the method of obtaining the statistical characteristics of the anomalous magnetic field over all the ocean profiles and for the aeromagnetic profiles on the continent [9], to solve the problem of similarity and difference of the statistical characteristics of the anomalous magnetic field for sections of the continent and ocean.

The parameter σ (Figure 2) is distributed most regularly. On the map it is quite clear that the increased values of this parameter are associated with the regions of the midocean rises. Thus, for example, the southern part of the Midatlantic Ridge, the western and eastern branches of the Indian seamounts have values of σ = 170-180 gammas. The deep sea trenches are characterized by reduced values of the parameter σ reaching about 100 gammas here. As for the very large values of σ = 220-250 gammas in the vicinity of the African-Antarctic Ridge on the Pacific Ocean seamount and also in the African-Antarctic and New Zealand trenches, this is obviously connected with the fact that the profiles of the hydromagnetic survey in these regions run along the linear anomalous zones.

From the graphs of $r_{0.3}$ (Figure 3) it is obvious that the minimum values of this parameter (5-6 km) are characteristic for the majority of midocean ridges if the survey profiles are run across the strike of the ridges. The deep water trenches located at significant distances from the axis of the ridges have values of $r_{0.3}$ for the same arrangement of the profiles with respect to the strike of the structures, three or four times greater than over the ridges themselves, and they are equal to 16-25 km.

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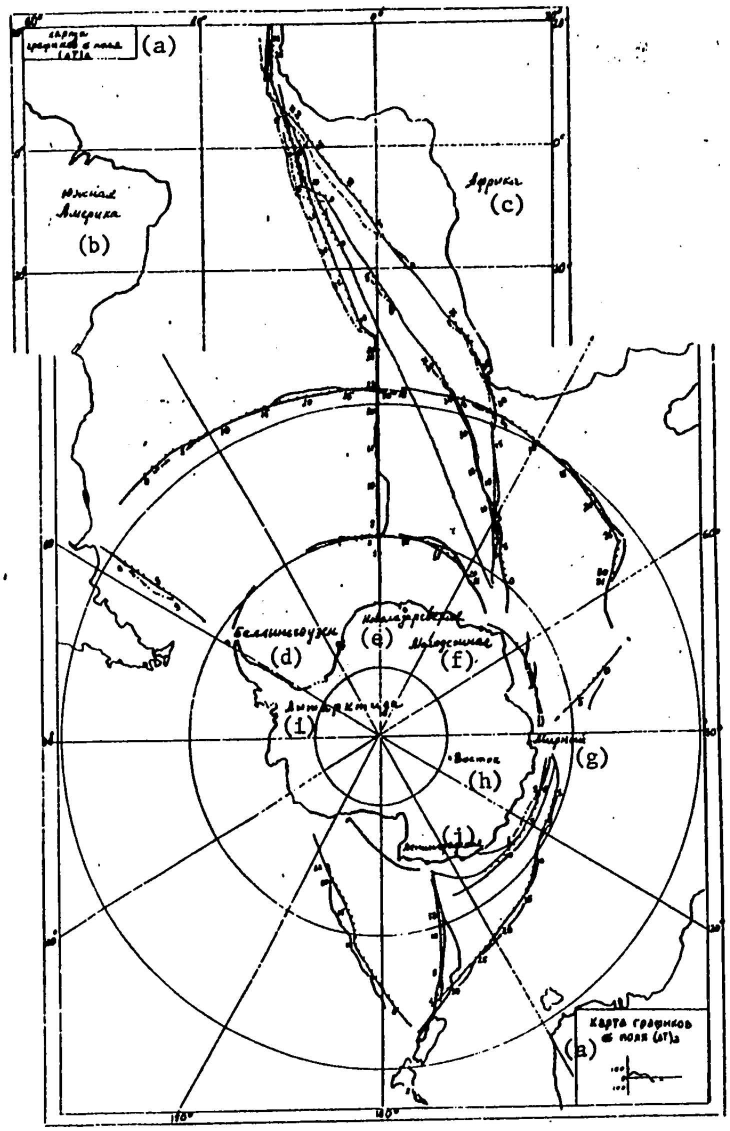

Figure 2.

Key:
- a. map of the graphs σ of the field $(\Delta T)_a$
- b. South America
- c. Africa
- d. Bellingshausen
- e. Novolazarevskaya
- f. Malodezhnaya
- g. Mirnyy
- h. Vostok
- i. Antarctica
- j. Leningradskaya

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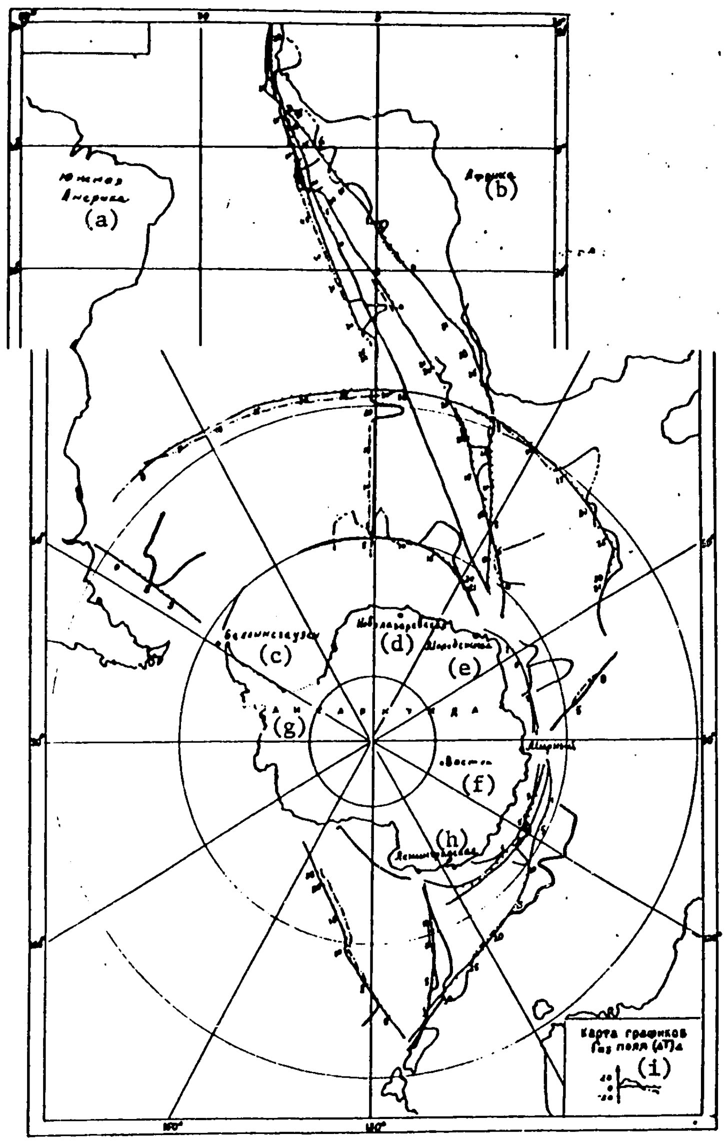

Figure 3.

Key:
- a. South America
- b. Africa
- c. Bellingshausen
- d. Novolazarevskaya
- e. Malodezhnaya
- f. Vostok
- g. Antarctica
- h. Leningradskaya
- i. map of the graphs of $r_{0.3}$ of the field $(\Delta T)_a$

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The slopes of the midocean ridges of seamounts occupy an intermediate position with respect to the values of σ and $r_{0.3}$.

Since the magnitude of the parameter $r_{0.3}$ is influenced by the direction of the profile with respect to the strike of the anomalies, when generalizing the results, the values of the correlation radius of the anomalous magnetic field were used which characterized the anomalous field along the profiles cutting defined structures across their strike.

In connection with the fact that the magnitude of some of the statistical parameters (especially the dispersion and correlation radius) is essentially influenced by the height of the magnetic survey with respect to the magnetic sources, it is necessary to reduce the obtained values to the identical relative level of the survey.

For this purpose the calculated mean statistical parameters of the anomalous magnetic field for profiles cutting the middle ridges across their strike were recalculated upward so that the recalculated values of the parameters gave a representation of the properties of the anomalous field on the same altitude with respect to the magnetic sources. The parameters σ and $r_{0.3}$ for the midocean ridges were recalculated to a height of $h = 2$ km, for the difference Δh between the average depth of the ocean over the ridge (~2 km) and the average depth above the trenches (~4 km) is about 2 km. The parameters of the anomalous magnetic field for the slopes were recalculated for $\Delta h = 1.5$ km, and Δh of the trenches was taken equal to zero. The parameters of the anomalous magnetic field for the coastal regions were not recalculated, for it is difficult to estimate the effect of the magnetically active sources of the ocean crust in this zone as a result of the presence of magnetic sources of the continental shelf.

If we approximate the correlation function of the anomalous magnetic field by an exponential-cosine function: $R = R_0 e^{-\alpha|\tau|} \cos \beta\tau$, in which the parameter α defines the rate of decrease of the function R, and the parameter β reflects the basic periodicity of the function, we obtain the following mean values of the parameters of the anomalous magnetic field for different provinces:

Ocean provinces	Statistical parameters	Before recalculation	After recalculation
Midocean ridges	R_0	32400 ^{2}	18225 ^{2}
	α	0.1 km^{-1}	0.08 km^{-1}
	β	0.14 rad·km^{-1}	0.12 rad·km^{-1}
	$r_{0.3}$	6 km	8 km
Slopes of the ridges	R_0	22500 ^{2}	1690 ^{2}
	α	0.7 km^{-1}	0.7 km^{-1}
	β	0.09 rad·km^{-1}	0.039 rad·km^{-1}
	$r_{0.3}$	9 km	13.8 km

In Figure 4 the relation is presented for the mean value of the parameter σ as a function of the distance to the center to the middle ridge with respect to isolated zones -- the solid line corresponds to the initial values of the parameter, and the dotted line, to the recalculated ones.

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In Figure 5 an analogous relation is presented for the parameter.

The upper solid line corresponds to the average values of the parameter $r_{0.3}$ with respect to all profiles, the lower solid line, with respect to the profiles cutting across the midocean ridges and the dotted line is the analog of the last curve recalculated upward.

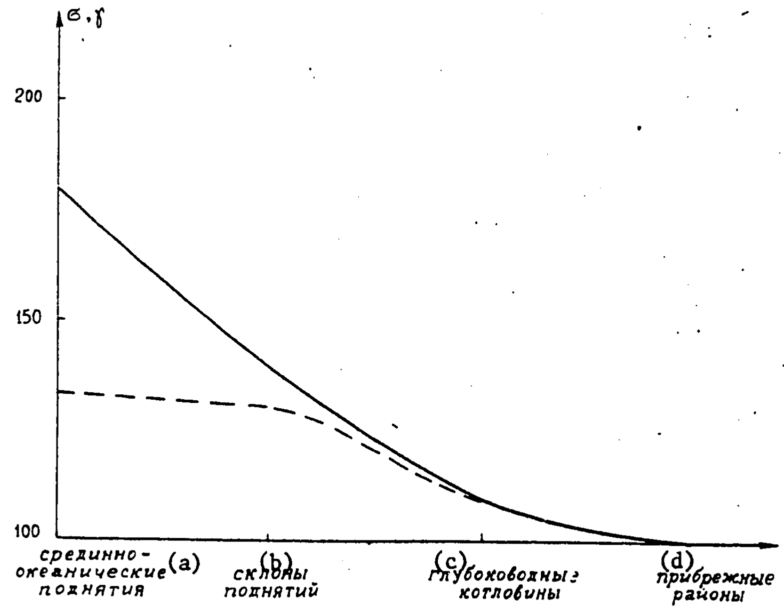

Figure 4. Graph of the statistical parameter σ.

Key: a. midocean rises
b. slopes of the rises
c. deep sea trenches
d. coastal regions

Since the parameter σ is a function of the degree of magnetization of the sources, it is possible to arrive at the conclusion that in the last ten million years the magnetization of the rock has decreased somewhat, and at a significant distance from the rise the rock formed several tens of millions of years ago has still less magnetization.

This conclusion finds its confirmation in reference [4], the authors of which, estimating the distribution of the natural residual magnetization of the ocean results and the dependence of the amplitudes of the ocean anomalies on the depth of the floor and on the distance to the axis of the midatlantic ridge arrive at an analogous conclusion: the decrease in the intensity of the magnetic anomalies on going away from the axis of the ridge is connected not only with an increase in depth of the floor, but, primarily, with variation of the nature of the sources of the anomalies.

The average values of $r_{0.3}$ of the anomalous magnetic field turned out to be equal to 6 km, 9 km and 20 km, respectively, for the middle ridges, slopes and trenches.

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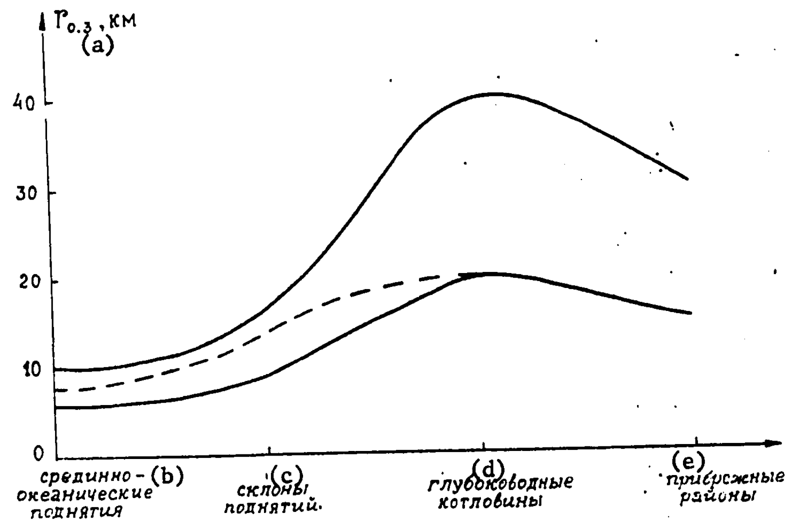

Figure 5. Graph of the correlation radius $r_{0.3}$

Key: a. $r_{0.3}$, km
b. midocean rises
c. slopes of the rises
d. deep water trenches
e. coastal regions

After recalculation of the survey for one altitude, new values turned out to be 8 km and 13.8 km, respectively, for the middle ridges and their slopes. This fact obviously indicates an increase in the horizontal dimensions of the blocks into which the ocean crust is broken on going away from the axis of the middle rise.

The unrecalculated values obtained for the parameters σ and $r_{0.3}$ coincide well with the analogous parameters of the anomalous magnetic field calculated in reference [4], in spite of the fact that the authors of this paper applied another procedure for estimating the statistical properties of the anomalous magnetic field: another model of the normal field, another (and inconstant) length of the investigated profile and an entirely different stepsize of the sampling of the field values $\Delta x = 0.5$ km. This indicates reliability of the results that we obtained and also that the sample of initial values of the field used by us ($\Delta x = 5$ km) was sufficient in the first approximation to discover the frequency properties of the field even in the vicinity of the midocean rises, for the difference in values of the parameter $r_{0.3}$ which we obtained in reference [4] does not exceed 1 to 1.5 km.

From what has been discussed above it follows that the statistical properties of the ocean are different for its different geomorphological provinces. Therefore it is expedient to compare individual uniform provinces of the oceans among each other, and these provinces with the uniform regions on the continents.

For example, if we compare the anomalous magnetic fields of the most ancient platforms (of the Siberian type) with the anomalous magnetic fields of the youngest midocean ridges, the difference in horizontal dimensions of the magnetic anomalies

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is isolated clearly (the median of the distribution of the parameter $r_{0.3}$ of the anomalous magnetic field of the Siberian platform is 22.5 km). This probably is connected with different horizontal dimensions of the blocks of the continental and ocean crust and, possibly, is defined by different thickness of the entire lithosphere within the limits of the compared regions. A comparison of analogous parameters for the same platform and deep water ocean trenches does not give a noticeable difference which obviously is caused by approximately identical thickness of the lithosphere of the compared regions.

In connection with the fact that the analysis of the anomalous magnetic field has great significance for the creation of new global tectonics (plate tectonics), we studied the anomalous magnetic field in the southern part of the Atlantic Ocean also from the point of view of the hypothesis of expansion of the ocean floor.

Two sublatitudinal profiles of the marine magnetic survey were subjected to analysis, the location of which is presented in Figure 6. From a comparison of the observed value of the field with the curves for the time variations of the field on the same days when the observations of the magnetic field were made along the profiles in Figure 7 it is obvious that the measurements were taken on days with undisturbed magnetic field.

Profile I (Figure 7) has the picture of the anomalous magnetic field which is typical of the midocean rises. As for profile II, although it is appreciably south of the South Atlantic ridge and in the bottom relief of the ocean in this part there is no significant rise as occurs in the vicinity of profile I, the picture of the anomalous magnetic field along profile II is astonishingly similar to that which is observed in profile I.

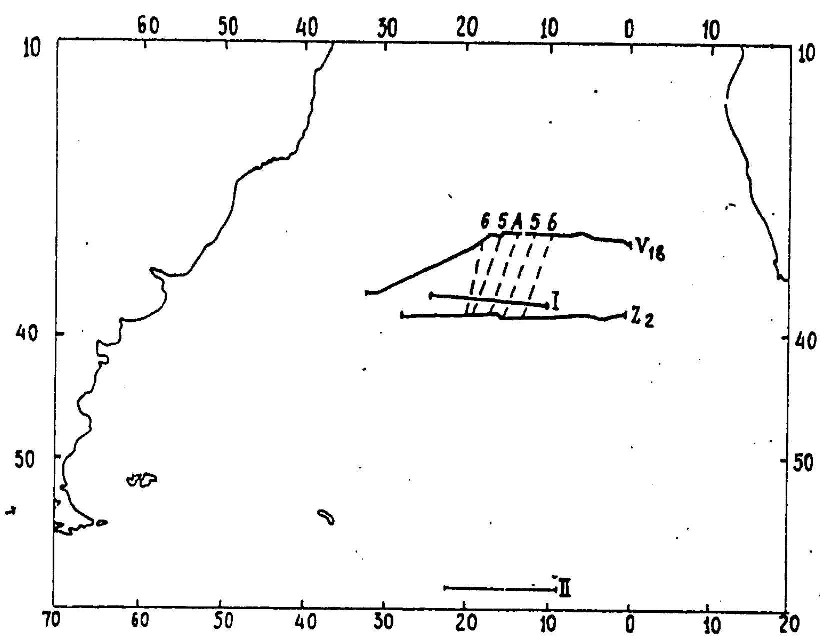

Figure 6. Location of profiles I and II.

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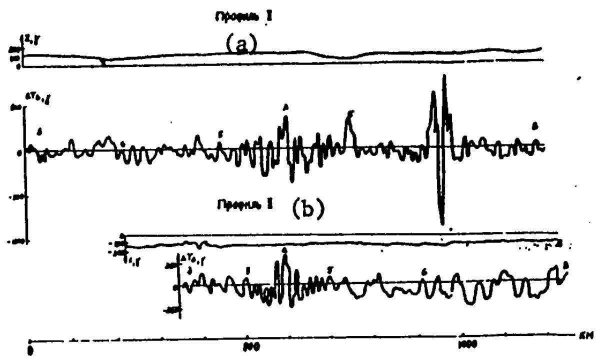

Graphs of T_H and T_a along the profiles I and II.

Key: a. profile I
b. profile II

Considering this fact and also based on the data on the seismic activity in the vicinity of profile II [10] and the presence in this region of a slight rise of the ocean floor, we have drawn the conclusion of a continuation of the South Atlantic Rise from Bouvet Island southwest in the direction of the Antarctic continent.

Thus, it is possible to consider that the rift system of the South Atlantic Ridge has its continuation to the southwest, and in the vicinity of Bouvet Island there is a node from which three rift systems radiate analogously to one which is observed in the center of the Indian Ocean. Estimates of the separation of the ocean floor made by profiles I and II confirm identical rate of separation of the ocean floor in the South Atlantic and in the vicinity of the southern Sandwich archipelligo.

Generalizing the results of the studies, it is possible to draw the following conclusions:

1. Regular variation of the statistical properties of the field in various parts of the World Ocean is demonstrated.

2. It is shown that the magnetization of the ocean rock and horizontal dimensions of the blocks of the ocean crust vary uniformly as a function of the distance to the axis of the ridges.

3. When comparing the spectral composition of the anomalous magnetic field of continents and oceans, differences are discovered in the spectrum of the midoceanic rises and ancient continental platforms, which indicates a difference in structure of the ocean and continental crust of these regions.

4. In the spectral composition of the ancient platforms and deep water trenches no noticeable difference is detected which indicates similarity in the structure of these regions and also that the thickness of the lithosphere under these structures in practice is identical.

5. The difference in frequency properties of the anomalous magnetic field does not disappear after recalculating the survey level for one altitude.

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6. On the basis of analysis of the constructed maps of the graphs, an effort is made at tectonic regionalization of the ocean floor.

7. A continuation of the South Atlantic Ridge to the southwest of Bouvet Island in the direction of the Antarctic continent was discovered, and the conclusion was drawn of the existence of a node in the vicinity of Bouvet Island from which three rift systems radiate.

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