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RADIO EMISSION OF SEA SURFACE AT CENTIMETER WAVELENGTHS AND ITS FLUCTUATIONS

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## GENERAL EXAMINATION

### Introduction

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As is known, radio emission of the sea is composed of its eigen thermal radio emissions and the radio emission of objects which surround the sea (the coastline, the atmosphere), which is reflected from the sea surface. We shall examine the eigen thermal radio emission of the sea. This is due to the fact that at centimeter wavelengths the reflected radio emission of the coast and the atmosphere is considerable only for small observation angles with the horizon. We shall also examine the agitated surface of the sea (the plane surface is examined for example in [1]), when the reflection (scattering) is similar in nature to diffused scattering. We may expect that the contribution of this emission to the total emission of the sea will be practically constant in time, and the time fluctuations of the radio emission of the sea will be basically determined only by a change in the eigen emission of the sea, connected with /4 the agitation.

In examining the eigen radio emission of the sea, we are interested in the value of the antenna response which is average in time ( $T_a$  - antenna temperature) to this radio emission and basically the change in this response with time (fluctuations). Naturally, these values depend on the form of the sea surface, the propagation velocity of the sea waves and the lengths, and also on the direction of observation and the antenna parameters (in particular, the relationship between the dimensions of a spot illuminated by the diagram on the surface of the sea  $d$  and  $d$ , on the one hand, and the lengths of a sea wave  $\Lambda$ , on the other hand; here  $d$  is the projection of the spot in the direction of the wave velocity, and  $d$  is its projection in the

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\*Numbers in the margin indicate pagination in the foreign text.

perpendicular direction).

Our problem is to find the response of the antenna (its time dependence, average dependence, and dispersion) to the eigen emission of the sea surface as a function of the parameters of the sea surface, the antenna, and the observation direction. To solve it, it is necessary to obtain the connection between the antenna temperature  $T_\alpha$  and the parameters of the antenna and the emitting surface. Secondly, given a certain model of the sea surface, we must calculate the time behavior of  $T_\alpha$ , the average, and the dispersion for the given parameters of the sea and the antenna.

1. Antenna response to thermal radio emission of the earth (sea)\* 5/

The response of the antenna  $T_\alpha$  to thermal radio emission of an object located in the zone of the Fraunhofer antenna is well expressed by the following well known relationship (see for example, the study [3]).

$$T_\alpha = \int_{\Omega_t} T_o F^2 d\Omega / \int_{4\pi} F^2 d\Omega, \quad (1)$$

where  $T_o$  is the brightness temperature of the object which determines the strength of the radiation leaving the object through its surface;  $F^2$  directional diagram of the antenna;  $\Omega_t$  solid angle of the object.

However, frequently, including observation of emissions from the sea, it is necessary to deal with a case when the sources of the emission are located in the antenna Fresnel zone. If the antenna dimension is  $D$ , and the wave length is  $\lambda$ , then the zone of Fresnel diffraction extends to a distance of  $r = D^2/\lambda$  from the antenna, and, for example,  $D = 10 \text{ m}$  and  $\lambda = 3 \text{ cm}$ ,  $r = 3 \text{ km}$ , whereas the radio emission from the sea is frequently observed from much closer distances. In this case, we may use the expression obtained in [2] following from the reciprocity theorem [4] or from the principle of detailed thermal dynamic equilibrium [5].

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\* The results obtained in [2] are used in this section.

$$T_0 = \frac{1}{\rho} \left\{ \oint_{f_t} T (\vec{S} \cdot \vec{n}) df + \int_{V_r} \vec{S} \operatorname{grad} T dv \right\}, \quad (2)$$

$\rho$  is the strength of the antenna;  $\vec{S}$  - the Poynting vector of the antenna field within the emitting object;  $\vec{n}$  - the normal to the surface  $f_t$  directed within the object.

Expression (2) makes it possible to reduce the problem of the reception of antenna thermal radio emission from different objects to the diffraction problem regarding distribution in these objects of the antenna field with antenna transmission operation\*[4] (relationship (1) follows from this expression with transfer into a remote zone).

When radio emission is received from the land and the sea, a constant temperature of the earth's surface is important (at least within the limits of the main blade of the diaphragm or several aerial apertures when the antenna is located close to the ground). Secondly, the total absorption of the power in the ground (sea) at a very small depth  $\sim (5-10) \lambda$  is very important even for dry ground (it is much less for the sea), where it can be assumed that the temperature is constant and equals the temperature on the surface  $T_0$ . Due to a constant temperature, expression (2) assumes the form

$$T_0 = \frac{T}{\rho} \int_{f_r} \vec{S} df, \quad (3)$$

where integration\*\* is performed over the external surface  $f_t$  (the value of  $S$  is taken "within"  $f_r$ , characterizing the energy passing into the earth).

Based on the relationship (3), we may speak equally about emission from the surface of the sea and the earth, whereas in the general case, the objects are emitting.

Thus to find  $T_0$  we must know the distribution of the Poynting vector of the antenna field with the surface  $f_t$  (the value  $\vec{S}$  "within"  $f_t$  may be found by knowing the incident field and  $\vec{S}$  on the surface  $f_t$ ).

\* We should note that equation (2) is valid only for the reception of thermal radio emission, since the thermal mechanism of emission is important in the derivation.

\*\* See section 3 regarding the integration limits

In the general case, this is exclusively a complex fraction problem, which can be solved only for the simplest types of surfaces. As regards uneven surfaces, this problem can be completely solved only for a plane uneven surface with roughnesses which are much less than the wave lengths  $\lambda$  [6-10], and with roughnesses which are large as compared with  $\lambda$  [11]. In the case of roughnesses which are much less than  $\lambda$ , the solution of the problem is reduced to examining the boundary conditions on a certain equivalent plane. This plane may be characterized by the effective values of the dielectric constant  $\epsilon_{app}$  and the conductivity  $\sigma_{app}$  [8,9], and we may use the effective reflection coefficient  $R_{app}$  [12].

When the roughnesses are much greater than the  $\lambda$ , according to the approximation of geometric optics [11], the field at each point of the surface is the same as if the reflection at this point came from an infinite plane which is tangent to the surface at this point. /8

In other words, it is assumed that on the surface an incident plane wave produces a reflected wave, which may be assumed to be approximately plane. The relationship between the incident and the reflected plane waves is given by means of the ordinary reflection coefficient of a plane wave, considering the inclination of the surface at this point. Thus, the field on the integration surface is determined by the approximation of geometric optics without considering the diffraction effects.

As applied to the scattering of acoustic and electromagnetic waves on an uneven surface, this method was considered in [11]. The assumptions lying at the basis of this theory may be transferred to a study of an unequal surface in accordance with relationship (3), where  $S$  is determined by the incident wave and the plane wave transmission factor.

The basic limitation of the method used in the study by Brekhovskikh is the form of the uneven surface. The nature of the unevenness must

be such that at each point of the uneven surface there may be a tangential plane which is at a distance of no more than the wave length  $\lambda$  from this surface. As shown in [11], this leads to the requirement that the following relationship holds between the radius of curvature  $\rho$ , the wave lengths  $\lambda$  and the slip angle  $\nu$  and

$$2\rho \cdot \sin \nu \gg \lambda / 2\pi, \quad (4)$$

and at the bending point ( $\rho \rightarrow \infty$ ) the following condition is calculated

$$\frac{1}{\sin \nu} \cdot \frac{\lambda^2}{6(2\pi)^2} \frac{d}{dx} \left( \frac{1}{\rho} \right) \ll 1,$$

where  $X$  is a coordinate determined along the middle level of the uneven surface.

(5)

For example, for a sinusoidal surface  $z = a \cdot \sin \frac{2\pi}{\lambda} x$  at the bending (on the inclination of the surface) we have the condition

$$[11] \quad \lambda^2 a / \Lambda^3 \ll \sin \nu, \quad (6)$$

In addition to the Brekhovskikh method, there are other approximate methods for determining the field on an uneven surface (for example, [13], [14]). However these methods refer to absolutely reflecting surfaces, and therefore cannot be used when examining emission.

In the study of the sea surface, we have used the approximation of geometric optics, assigning a certain model for the sea surface.

## 2. Models of the sea surface

The structure of the sea surface is very complex, since there are wind waves in the sea with different amplitudes and velocities, which interact, and also interact with waves reflected from the shore\*.

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The wind waves have a different form depending upon their development. In addition, there are always small waves on the surface of the large waves. Finally, the profile of the waves and the

\* In addition to wind waves, there are very long waves and tidal waves with a large period, which we do not consider.

relationship between its velocity  $C$  and the wind velocity  $V$  depends on the depth of the sea.

To obtain a qualitative picture and the necessary quantitative estimates, it is advantageous to consider the simplest models of a sea surface, as which we may use a regular moving structure (wave) and a surface which changes randomly in time with a given law governing the distribution of the areas for a given inclination of each area to the horizon.

Let us first consider a regular moving surface.

It is known [15] that in the stage of development and brief growth, and also in the stage of powerful storm swells, there are "two dimensional" waves, i.e., waves whose profile does not change in a direction perpendicular to the wave velocity vector. In the intermediate stages the swells as a rule become "three dimensional". Thus we shall examine two possible forms for a regular moving surface of the sea.

Since we are interested in the maximum fluctuations of the sea radio emission, connected with the swells, we shall examine the largest waves. As shown in [15], these waves (two dimensional and three dimensional) may be approximated by the relationships

$$\left. \begin{aligned} x &= \frac{\Lambda}{2\pi} \theta_1 + \alpha \sin \theta_1 - ct \\ z &= h \cos \theta_1 \end{aligned} \right\} \quad (7a)$$

where  $\Lambda$  is the wave length;  $C$  - its velocity (we consider a wave which moves in a direction opposite to the  $X$  axis);  $h$  - amplitude; /11

$$\alpha = 0,112 \Lambda;$$

$$h = 0,0715 \Lambda \quad (h/\Lambda = 0,45).$$

The maximum inclination of this surface to the horizon is  $\approx 30^\circ$ .

The three dimensional waves

$$z = h \cos \frac{2\pi}{\Lambda} (x + ct) \cos \frac{2\pi}{L} y, \quad (7b)$$

where  $h = 0,078 \Lambda$  ( $k h = 0,5$ ) or

$$h = 0,04 \Lambda \quad (k h = 0,25).$$

i.e., we consider a three dimensional wave with the maximum amplitude and the largest angle of inclination to the horizon of about  $30^\circ$ , and also a wave with half the amplitude and the largest angle of inclination to the horizon of about  $15^\circ$ .

According to [15]  $c_1 = c \sqrt{1 + \left(\frac{\Lambda}{L}\right)^2}$ . We assume that  $L = \Lambda$  i.e.  $c_1 = 1,19 c$ , but for simplicity we shall assume  $c_1 = c$ . The velocity of a wind wave is connected with the wind velocity  $V$  by the relationship  $c = 0,76 V$ . [15].

The wave length  $\Lambda$  is connected with the velocity  $C$  and consequently with the wind velocity.

$c = \sqrt{g \Lambda / 2\pi}$  for a depth of the sea  $H$  which is much greater than  $\Lambda$ . However, as shown in [16] this relationship between  $C$  and  $\Lambda$  is satisfied even at  $H/\Lambda = 0,2$  with an error of about 8%.

Therefore we shall assume

$$c = \sqrt{g \Lambda / 2\pi}. \quad (7c)$$

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Thus the parameters of the sea surface depend only on the wind velocity. Taking this into account, we may write the expression for the models of the sea surface (wind velocity  $V$  in meters per second):

Two dimensional surface

$$\begin{cases} x = \frac{0,37 v^2}{2\pi} \theta, + 4,15 \cdot 10^{-3} v^2 \sin \theta, - 0,76 vt, \\ z = 2,6 \cdot 10^{-2} v^2 \cos \theta, \end{cases}$$

Three dimensional surface

$$\begin{aligned} z_1 &= 2,92 \cdot 10^{-2} v^2 \cos \frac{2\pi}{0,37 v^2} (x + 0,76 vt) \cos \frac{2\pi}{0,37 v^2} y; \\ z_2 &= 1,46 \cdot 10^{-2} v^2 \cos \frac{2\pi}{0,37 v^2} (x + 0,76 vt) \cos \frac{2\pi}{0,37 v^2} y. \end{aligned}$$

Considering that the time period of a sea wave

$$T = \frac{\Lambda}{c} = \frac{0,37 v^2}{0,76 v} = 0,487 v,$$

we have the following for a two dimensional wave

$$x = \frac{0.37v^2}{2\pi} \theta_1 - \frac{0.37v^2}{2\pi} 2\pi \frac{t}{T} + 4.15 \cdot 10^{-2} v^2 \sin \theta_1 ;$$

$$z = 2.6 \cdot 10^{-2} v^2 \cos \theta_1 ;$$

and for a three dimensional wave

$$z_1 = 2.02 \cdot 10^{-2} v^2 \cos \left( \frac{2\pi}{0.37v^2} x + 2\pi \frac{t}{T} \right) \cos \frac{2\pi}{0.37v^2} y .$$

or

$$z_2 = 1.46 \cdot 10^{-2} v^2 \cos \left( \frac{2\pi}{0.37v^2} x + 2\pi \frac{t}{T} \right) \cos \frac{2\pi}{0.37v^2} y .$$

Considering the approximations used regarding the relationship between the wind velocity and the wave length and the period for different wind velocities corresponding to different points on the Beaufort scale [16], we have the approximate values of  $\Lambda$  and  $T$  given in Table I.

Using (6), we obtained the condition for the applicability of the method of geometric optics (we assume the surface is sinusoidal and  $h \approx 0.1\Lambda$ )

$$0.1 \frac{\Lambda^2}{\lambda^2} \ll \sin \vartheta_1 \tag{8}$$

which gives the following at  $\lambda=3$  and  $\Lambda=3$  (the swells are less than three points)  $\sin \vartheta_1 \gg 10^{-5}$ , i.e.  $\vartheta_1 > 1'$

Thus the method of geometric optics may be used for any observation directions, with the exception of tangents to the surface, i.e., the region of angles with the horizon of  $\theta_1 = 25-30^\circ$  and  $\theta_1 = 15^\circ$  (the latter is for a surface with half of the amplitude)\*.

\*At  $\theta_1 < 30$  or  $15^\circ$  for individual points of the surface  $\vartheta_1 = 0$ . However the contribution of these regions to the total radio emission is small, whereas at  $\theta_1 = 30^\circ$  or  $15^\circ$  for practically the entire inclination of a wave which "trails" with respect to the observation point  $\vartheta_1 = 0$ .

For angles which are less than the angle of the maximum inclination of the surface to the horizon, it is necessary to introduce the shading function of parts of the surface by other parts. We must also consider the reflection of radio emission of one side of the wave from the other.

When using the method of geometric optics, it is necessary to know the reflection factors from the sea surface  $R$ , determined by the value of its dielectric constant  $\epsilon = \epsilon' + i\epsilon'' (\mu = 1)$  (9)

Table I

parameters	points											
	I	2	3	4	5	6	7	8	9	10	11	12
V, m/sec.	0.6- 1.7	1.8- 3.3	3.4- 5.2	5.3- 7.4	7.5- 9.8	9.9- 12.4	12.5- 15.2	15.3- 18.2	18.3- 21.5	21.6- 25.1	25.2- 29	29
② $\lambda$ , m per sec.	0,1-1	1-4	4-10	10-20	20-36	36-56	56-85	85- 120	120- 170	170- 230	230- 300	300
③ $T$ , sec.	0,05- 0,8	1- 1,6	1,65- 2,53	2,6- 3,6	3,7- 4,8	5-6	6- 7,5	7,5- 9	9-10	10- 12	12-15	15

Introducing the notation  $\rho = \beta - \rho'$ , we may use  $|\rho| = 65$ ,  $\rho' = 8$  into calculations (see [8]).

As another possible model of a sea surface, let us examine a surface which changes at random in time and in space with a random distribution of the angles of inclination of the surface to the horizon  $\theta$ .

We shall consider the two dimensional and three dimensional stochastic models of the surface. We shall characterize them by the

normal law of distribution P of the angles of inclination  $\theta$  with different mean square values of  $\sigma$ , from 2 to 15°.

Let us give the space-time and characteristics of the models. We shall characterize the two dimensional model by a two dimensional distribution density of the angles of inclination in the form

$$\rho(\theta_1, \theta_2) = \frac{1}{2\pi\sigma_0 [1-\rho_0^2(u)]^{1/2}} \exp\left[-\frac{\theta_1^2 + \theta_2^2 - 2\rho_0(u)\theta_1\theta_2}{2\sigma_0^2 [1-\rho_0^2(u)]}\right], \quad (10)$$

where  $\rho_0(u)$  - is the normed correlation function of the angles of inclination;  $[\rho_0(0)=1]$  three dimensional  $(u = \tau)$  or  $(u = \tau)$ .

Let us consider stochastic surfaces which are characterized by the correlation functions of the form:

$$\rho_0(u) = \exp\left[-\alpha_0 \frac{|u|}{U}\right] \cos \frac{2\pi}{U} u, \quad (11a)$$

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$$\rho_0(u) = \exp\left[-\left(\frac{u}{U_0}\right)^2\right]. \quad (11b)$$

Expression (11a) characterizes the correlation properties of a random process with the quasiperiodic component [18] and is a stochastic analog of the regular two dimensional model. Such a surface is distinguished by an average period of the waves  $(U = \bar{T}_\lambda)$ , and the average wave length  $(U = \bar{\lambda})$ . The coefficient  $\alpha_0$  is the index of the irregular swells.

We shall use the correlation function of the form (11b) to characterize a random process without a quasiperiodic component of the ripple type.

We may determine the space-time characteristics of the emission

field for a three dimensional model from the data for a two dimensional model and the assumption of the separation of the variables along the  $Ox$  and  $Oy$  axes in the expression for the correlation function of the emission capacity of the surface  $\rho_{\alpha}(u_x, u_y)$ . Thus, we shall characterize the stochastic three dimensional model with a quasiperiodic component along the  $Ox$  and  $Oy$  axes, similar to the two dimensional model for given  $\rho_0(u)$  in the form (11a), by the average wave length  $\bar{\lambda}$  (the average period  $\bar{T}_\lambda$  along the  $Ox$  axis, and the average length of the crest  $\bar{L}$  along the  $Oy$  axis. The coefficient  $\nu = \frac{\bar{L}}{\bar{\lambda}}$  characterizes the three dimensionality of the swell. In the case of isotropic swells  $\nu = 1$ .

### 3. Certain notes regarding the integration and polarization region

The integration region is determined by an illuminated spot on the surface of the sea, i.e., in the case of a formed diagram - by the intersection of the main blade of the diagram with the sea surface, since we are only interested in the power received by the main blade of the diagram\*. Therefore in expression (3)  $S$  is proportional to the power emitted by the antenna in the main blade, i.e., the quantity  $\rho(1-\beta_{sa})$ , where  $\beta_{sa}$  is the antenna scattering coefficient [1]. In addition, since we use the stream density in expression (3), we will place the coefficient  $1/\sigma_s$  in front of the integral, where  $\sigma_s$  is the transverse cross section of the main diagram blade at the point of intersection with the sea surface.

When the emitting surface is located in the Fresnel zone (at a distance of  $r < D^2/\lambda$  from the antenna), instead of  $(1-\beta_{sa})$ , as was shown in [2] we must use the quantity  $(1-\beta_s)$  at  $r < D^2/(10-25)\lambda$  or  $(1-\beta_s - \beta_{sa}/4)$  at  $D^2/\lambda \gg r > D^2/(10-25)\lambda$ , where  $\beta_s$  is the antenna scattering coefficient in semi-space. The integration region is thus

\* It may be readily seen that a change in the antenna temperature during the reception of radio emission may only occur due to the fluctuations of the emission incident on the main blade, whereas the fluctuation of the radio emission of the sea, incident on the side blades is due to a wide "lateral" diagram. In addition in relative measurements the background radio emission is practically excluded.

determined as the intersection with the sea surface and a cylindrical wave beam, whereas cross section linear dimensions are (3+ 5) D. Physically, this follows from the qualitative picture where the formation of the antenna directional diagram examined in [2]. /18

The reflection coefficient R of any surface as is known depends on the polarization of incident emission with respect to the surface, i.e., and further, the electric vector of the incident field is located in the plane of incident or is perpendicular to it (we should recall that the plane of incident at a given point of a surface refers to the plane passing through the normal to the surface at a given point  $\vec{n}$ , and the Poynting vector of the incident field  $\vec{S} = |S| \cdot \vec{t}_0$ , where  $\vec{t}_0$  - the unit vector). At the same time, the polarization of the antenna is determined with respect to the plane surface of the earth. It is therefore clear that where a given polarization of the receiving antenna (horizontal H or vertical V) at any point of the surface in the general case there will be both polarizations with respect to the surface at a given point) designated later by the indices  $v, r$  - vertical and horizontal), in accordance with the projections of the electric served vector on the plane of incident and on the plane perpendicular to it. Consequently  $T_{ov}$  (the antenna response in the case of its vertical polarization) will depend not only on  $R_v$ , but also on  $R_r$  (similarly to  $T_{oh}$ ). This phenomenon is somewhat arbitrarily called D polarization, since when receiving emission from a agitated surface the difference  $\Delta T_{ov,h}$  between  $T_{ov}$  and  $T_{oh}$  in the general case is smaller than  $\Delta \bar{T}_{ov,h}$  when receiving emission from a plane surface of the sea, when  $T_{ov}$  and  $T_{oh}$  depend only on  $R_v$  and  $R_r$ . /19

#### 4. Specific expression for antenna response to emission from a rough surface

Let us consider a rectangular coordinate system  $Ox, Oy, Oz$

(the unit vectors  $\vec{i}, \vec{j}; \vec{k}$ ) with the plane  $xy$ , coinciding with the plane surface of the sea (Fig. 1). We shall assume that the antenna is located at the point  $A(0,0,H)$  of the Z axis at the height  $H$  above the plane  $x, y$ , and the receiving direction (emission) will be characterized by the unit vector  $\vec{t}_0$

$$t_{0x} = \sin \vartheta \cos \varphi; \quad t_{0y} = \sin \vartheta \sin \varphi; \quad t_{0z} = \cos \vartheta$$

- are the directional cosines (the angle  $\varphi$  - the azimuth - is read from the X axis; the angle  $\vartheta$  - the zenith angle - is read from the Z axis).

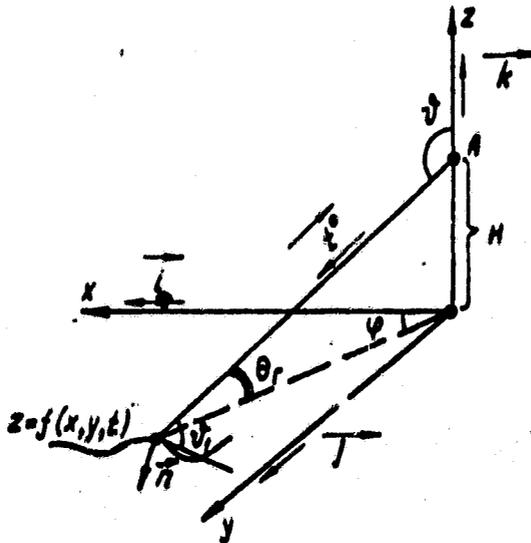


Figure 1

The emitting surface may be given in the form  $x=x(\theta, t), z=z(\theta, t)$  or in the form  $z=f(x, y, t)$  in accordance with (7), or as a random  $z=z(x, y)$ , where  $z(x, y)$  is a function which randomly changes in time and space.

The normal to the surface  $\vec{n} (|\vec{n}|=1)$  has the components

a)

$$\left. \begin{array}{l} x = x(\theta, t) \\ z = z(\theta, t) \end{array} \right\} \begin{array}{l} n_x = \frac{\partial z / \partial \theta_1}{\sqrt{\left(\frac{\partial z}{\partial \theta_1}\right)^2 + \left(\frac{\partial x}{\partial \theta_1}\right)^2}} ; \\ n_y = 0 ; \\ n_z = \frac{-\partial x / \partial \theta_1}{\sqrt{\left(\frac{\partial z}{\partial \theta_1}\right)^2 + \left(\frac{\partial x}{\partial \theta_1}\right)^2}} ; \end{array}$$

b)

$$\left. \begin{array}{l} z = f(x, y) \end{array} \right\} \begin{array}{l} n_x = \frac{\partial f / \partial x}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1}} ; \\ n_y = \frac{\partial f / \partial y}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1}} ; \\ n_z = \frac{-1}{\sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1}} ; \end{array}$$

The element of the surface  $df$  equals:

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a)

$$df = \sqrt{\left(\frac{\partial z}{\partial \theta_1}\right)^2 + \left(\frac{\partial x}{\partial \theta_1}\right)^2} \cdot d\theta_1 \cdot dy$$

b)

$$df = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + 1} \cdot dx \cdot dy$$

The reflecting (emitting) properties of the surface, as was already shown, will be characterized by the reflection coefficients at each point for the vertical  $R_v$  and horizontal  $R_h$  polarization (with respect to the surface at the given point).

$$\begin{aligned} |R_v|^2 &= \frac{|\rho|^2 (\vec{t}_0 \vec{n})^2 - 2\rho' (\vec{t}_0 \vec{n}) + 1}{|\rho|^2 (\vec{t}_0 \vec{n})^2 + 2\rho' (\vec{t}_0 \vec{n}) + 1}, \\ |R_h|^2 &= \frac{|\rho|^2 - 2\rho' (\vec{t}_0 \vec{n}) + (\vec{t}_0 \vec{n})^2}{|R_v|^2 + 2\rho' (\vec{t}_0 \vec{n}) + (\vec{t}_0 \vec{n})^2}, \end{aligned} \quad (12)$$

where  $|\rho|$  and  $\rho'$  are determined by expression (9);

$$(\vec{t}_0 \vec{n}) = \sin \vartheta_0;$$

Here  $\vartheta_0$  is the slip angle to the surface.

In equation (12), we disregard the quantity  $\cos^2 \vartheta_0$ , as compared with  $|\rho|^2 = |\epsilon|$ , since  $|\rho|^2 \gg 1$ .

Allowance for depolarization is reduced to projecting the electric vector  $\vec{E}$  of the incident field on the incidence plane and on the perpendicular to it. Thus the expression for the emission coefficient has the form

$$\alpha_{v,h} = 1 - |R_{v,h}|^2 = (|R_v|^2 - |R_h|^2) \cos^2 \alpha, \quad (13)$$

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where the signs "-", "+" and the indices "v" and "h" refer to "v" and "h";

$\cos^2 \alpha$  which considers depolarization is given by the following relationship:

at  $t_{\alpha} \neq 1$

$$\cos^2 \alpha = \cos^2 \alpha = \frac{([\vec{k} \vec{t}_0][\vec{t}_0 \vec{n}])^2}{\{1 - (\vec{t}_0 \vec{k})^2\} \{1 - (\vec{t}_0 \vec{n})^2\}}; \quad (14a)$$

5

$$\cos^2 \alpha = \frac{(\vec{t}_0 \vec{n})^2}{1 - n_2^2}, \quad (14b)$$

where  $\vec{t}_y(\cos \varphi, \sin \varphi, 0)$  is the unit vector in the X plane  
y ;

$$\cos^2 \alpha = \frac{(\vec{t}_y \vec{n})^2}{1 - n_z^2} ,$$

where  $\vec{t}_y \{ \cos(\varphi + \frac{\pi}{2}), \sin(\varphi + \frac{\pi}{2}), 0 \}$  is the

unit vector in the X,Y plane at  $\vec{t}_0 \parallel \vec{n}$

$$\cos^2_{y,H} \alpha = 0 . \quad (14c)$$

We consider the shading of part of the surface by introducing the shade function  $\eta(x, y, t)$ , which equals zero in the shade regions and equals unity outside of these regions. /23

Thus for  $T_{ay}$  and  $T_{aH}$ , according to (3), we have the following relationships

$$T_{ay,H} = (1 - \beta) T_{s,y,H}, \quad T_{s,y,H} = T_0 \alpha_{d,y,H} , \quad (15)$$

where:

- in the case of parametric determination of the surface in the form of "two dimensional" waves

$$\alpha_{d,y,H} = \frac{1}{\sigma_d} \int (t_{ox} \frac{\partial z}{\partial \theta_x} - t_{oz} \frac{\partial x}{\partial \theta_x}) \alpha_{y,H} \eta d\theta_x d\theta_y \quad (16a)$$

- when determining the surface in the form  $z = f(x, y, t)$

$$\alpha_{d,y,H} = \frac{1}{\sigma_d} \int (t_{ox} \frac{\partial f}{\partial x} + t_{oy} \frac{\partial f}{\partial y} - t_{oz}) \alpha_{y,H} \eta dx dy . \quad (16b)$$

The expressions (15)-(16) depend on the antenna parameters, the integration region and  $\sigma_d$ , on the receiving direction  $\vec{t}_0$  and on the parameters of the sea surface  $f, \rho, \cos \alpha$ . The illuminated spot is determined by the quantities  $\lambda, H$  and  $D$ , where  $D$  are the linear dimensions of the antenna opening. The receiving direction is determined by the angles  $\varphi$  and  $\theta_r$ , and the properties of the sea surface (in addition to its form  $f$ ), by the value of  $\varepsilon$ , and the values of the wind velocity  $V$ .

Expressions (15)-(16) make it possible to find the dependence of  $\sigma_{v,A}^t$ ,  $T_{v,A}^t$ ,  $T_{0v,A}^t$  on time t for different values of these parameters  $(\lambda, H, D, \psi, \theta, \epsilon, \nu)$  \*

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From these expressions, we may readily obtain the average value  $\bar{\sigma}^t$ ,  $\bar{T}_A^t$ ,  $\bar{T}_0^t$  and the dispersion of the fluctuations  $\overline{\delta\sigma^t}$ ,  $\overline{\delta T_A^t}$ ,  $\overline{\delta T^t}$  of the emission capacity of a rough surface, the brightness and antenna temperatures.

Let us determine the interrelationship between the characteristics of the emission and the parameters of the stochastic model of the surface.

The average value of the emission capacity of the surface, formed by a steady state random function, is determined in the general case as the mathematical expectation using the formula

$$\bar{\sigma}_{v,A}^t = \frac{1}{\int_{\Omega} \rho(F_n) \eta dF_n} \int_{\Omega} \sigma_{v,A} \rho(F_n) \eta dF_n. \quad (17)$$

Here  $F_n$  in the general case is a two dimensional vector which characterizes the orientation of the normal  $\vec{n}$  to an element of the surface; for a two dimensional model  $\rho(F_n) = \rho(\theta)$ , for a three dimensional model  $\rho(F_n) = \rho(\theta, \psi)$ ,  $\theta$  - angle of inclination;  $\psi$  - azimuth of the normal  $\vec{n}$ ;  $\Omega$  - region of values of  $F_n$ : for a two dimensional model  $\frac{\pi}{2} \leq \theta \leq \frac{3\pi}{2}$ ; for a three dimensional model  $0 \leq \theta \leq \frac{\pi}{2}$ ;  $0 \leq \psi < 2\pi$ . In the case of a three dimensional isotropic model  $\rho(\theta, \psi) = \rho(\theta)$  for all values of the azimuth  $0 \leq \psi < 2\pi$ .

Using (12) and (17), we obtain the dispersion of the emission coefficient fluctuations from the expression:

\* We should note that expressions (15) and (16) do not consider the emissions of the wave slopes reflected from the adjacent slopes. For a model of the sea surface with the maximum inclination  $30^\circ$ , the emission reflected from the adjacent slopes is possible at  $150^\circ > \theta > 120^\circ$ , where we may introduce the corresponding correction.

$$\sigma_{\alpha_{l,e}}^2 = \overline{\delta \alpha_{l,e}^2} = \frac{1}{\int_{\theta_r} P(F_n) \eta dF_n} \int_{\theta_r} (\alpha_{l,e} - \bar{\alpha}_{l,e})^2 P(F_n) dF_n. \quad (18)$$

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Expressions (14), and (18) make it possible to determine the average value, and also the dispersion of the fluctuations in the emission capacity and the brightness temperature without considering the finite dimensions of the emitting section of the surface.

Let us obtain the analytical expression for the dependencies of the emission characteristics  $\bar{\alpha}$  ( $\sigma_e, \theta_e$ ),  $\sigma_{\alpha}$  ( $\sigma_e, \psi_e$ ) on the sea parameter  $\sigma_e$ , for different values of the angle of the observation  $\theta$  for a two dimensional surface model at  $\varphi = 0^\circ$  ( $\theta_e = \frac{\pi}{2} - \theta_r$ ).

An analysis of the angular dependencies  $\alpha_{l,e}(\psi_e) = 1 - |\rho_{l,e}(\psi_e)|^2$  for calculated and experimental, shows the possibility of approximating them with functions of the form

$$\alpha_{l,e}(\psi) = \alpha_0 \pm A_{l,e} \psi_0^2 \quad (19)$$

in the interval of values  $0 \leq \psi_0 \leq \frac{\pi}{2}$  for horizontally polarized  $0 \leq \psi_0 < \psi_e$  and for vertically polarized emission, where  $\psi_e$  is the booster angle. The signs "+" and "-" are taken for the indices "e" and "h" ( $\psi_0 = \frac{\pi}{2} - \psi_e$ ).

The accuracy of the quadratic approximation can be determined by differentiating the expressions for the emission coefficients  $\alpha_{l,e}(\psi_0)$  with respect to the angle  $\psi_0$ . It follows from analyzing the expression for the derivatives  $s_{\alpha_{l,e}}(\psi_0) = \frac{d\alpha_{l,e}(\psi_0)}{d\psi_0}$  that the functions  $\alpha_{l,e}(\psi_0)$ , determined by expressions (10), (12) and (19), for horizontal polarization in the wave length range  $\lambda$  from 1 to 30 cm coincide within an accuracy which is no worse than 3%. This means that  $s_{\alpha}(\psi_0, \lambda) = k_2(\lambda) \psi_0$ , which corresponds to the derivative of the function (19), where  $k_2(\lambda) = 2A_2(\lambda)$ .

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For vertical polarization (and horizontal at the wave length  $\lambda = 0.87$  cm)

the maximum deviations of the approximating function from the dependence  $s_{\theta, z}(\psi)$  according to (10), (12) represent a quantity which is no more than 10%. Thus with this accuracy  $s_{\theta, z}(\lambda, \psi_0) \approx k_{\theta, z}(\lambda) \psi_0$ . The values of the coefficients  $A_{\theta, z}$  used in the calculations for different wave lengths are given in Table 3.

When using the distribution density of the angles of inclination  $P(\theta)$  in the form of a normal law, according to the assumed surface model and the quadratic approximation of the dependents  $s_{\theta, z}(\psi)$ , we obtain the following expressions for the average value and the dispersion of the fluctuations of the emission capacity:

$$\bar{s}_{\theta, z} = s_0 \pm A_{\theta, z}(\lambda) \sigma_0^2 (2a^2 + 1), \quad (20)$$

$$\sigma_{s_{\theta, z}}^2 = 2A_{\theta, z}^2(\lambda) \sigma_0^4 (4a^2 + 1), \quad (21)$$

where  $a = \theta_0 / \sqrt{2} \sigma_0$ ,

and the corresponding values of the brightness temperature:

$$\bar{T}_{\theta, z} = T_0 \bar{s}_{\theta, z}; \quad (20')$$

$$\sigma_{T_{\theta, z}} = \delta T_{\theta, z} = T_0^2 \sigma_{s_{\theta, z}}; \quad (21')$$

In formal terms expressions (20), (21) are valid in a range of the observation angles  $\theta_0$ , excluding the shading of a portion of the surface. Considering the characteristics of the dependents  $s_{\theta, z}(\psi)$  for vertical polarization (Brewster angle), this range may be determined approximately from the following condition

and

$$\theta_0 + 3\sigma_0 \leq \begin{cases} \theta_0 & \text{for vertical polarization} \\ \frac{\pi}{2} & \text{for horizontal polarization} \end{cases} \quad (22)$$

However, an analysis shows that when determining the radiation properties of an uneven surface the function  $P(\theta)$  in (17), (18)

is the distribution density of the angles of inclination determined with respect to the observation direction  $\rho(\theta/\theta_0)$ . It is necessary to consider the dependence of the distribution density of the angles of inclination on the angle  $\theta_0$ , at which the observation is performed, particularly values of  $\theta_0 > 40^\circ$ . We may show that this dependence is considered by introducing the correcting function

$$\rho_A(\theta, \theta_0) = \frac{\cos(\theta - \theta_0)}{\cos \theta}, \quad (23)$$

so that

$$\rho(\theta/\theta_0) = q \rho(\theta) \rho_A(\theta, \theta_0)$$

where  $q$  is the norming factor.

We should note that according to (19) and (21)

$$\frac{\sigma_{x_{1,2}}(\lambda_1)}{\sigma_{x_{1,2}}(\lambda_2)} = \frac{A_{x_{1,2}}(\lambda_1)}{A_{x_{1,2}}(\lambda_2)} \quad (24)$$

for fixed values of  $\theta_0$  and  $\sigma_\theta$ .

To determine the emission characteristics considering the parameter  $\sigma_\theta$ , which characterizes the dimension of the transverse cross section of the main diagram blade at the point of intersection with the surface, and to obtain the expression for the dispersion of the antenna temperature fluctuations, it is necessary to use data on three dimensional and time properties of the surface models. /28

For a two dimensional model, the correlation function of the emission capacity  $P_2(u)$  is determined by substituting (10) into the expression

$$P_2(u) = \iint_{Q_2} x(\theta_1) x(\theta_2) \rho(\theta_1, \theta_2, u) d\theta_1 d\theta_2 \quad (25)$$

where  $Q_2$  is the region of values of  $\theta$ , and  $\theta_{0,2} = \theta_{1,2} + \theta_0$

In the case of quadratic approximation of the dependence  $x(\theta_0)$  in the form of (19) an integration in infinite limits, will obtain

$$P_{x_{1,2}}(u) = A_{x_{1,2}}^2 \iint_{-\infty}^{\infty} \frac{(\theta_1 + \theta_0)^2 (\theta_2 + \theta_0)^2}{2\pi \sigma_\theta^2 [1 - \rho_\theta^2(u)]^{1/2}} \exp\left\{-\frac{\theta_1^2 + \theta_2^2 - 2\rho_\theta(u)\theta_1\theta_2}{2\sigma_\theta^2 [1 - \rho_\theta^2(u)]}\right\} d\theta_1 d\theta_2 =$$

$$= 4A_{x_{1,2}}^2 \sigma_\theta^4 \left\{ \sigma_\theta^2 + \sigma_\theta^2 [1 + 2\rho_\theta(u)] + \frac{1}{4} [1 - 2\rho_\theta^2(u)] \right\}, \quad (25')$$

where  $\sigma = \frac{\theta_0}{\sqrt{2} \sigma_\theta}$ .

The sign of the approximate equality is explained not only by the selected approximation of the dependence  $\varepsilon(\nu_0^2)$ , but also by the Gaussian approximation of the distribution density  $\rho(\theta_1, \theta_2)$  and integration in infinite limits. It is apparent that the error will be smaller, the smaller is the value of  $\sigma_\theta$ . When deriving (20), (21), it is assumed that there is no shading of surface areas, i.e., condition (22) is satisfied.

We determine the following from (25'):

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- the normed correlation function of the emission capacity and the brightness temperature in the form

$$\rho_{\varepsilon, \varepsilon'}(u) = \rho_{A, A'}(u) = \frac{1}{4\sigma^2 + 1} [4\sigma^2 \rho_\theta(u) + \rho_\theta^2(u)] \quad (26)$$

or

$$\rho_{\varepsilon, \varepsilon'}(u) = \frac{1}{2m^2 + (\sigma'_\theta)^2} [2m^2 \rho_\theta(u) + (\sigma'_\theta)^2 \rho_\theta^2(u)] \quad (26')$$

where  $m = \frac{\theta_0^0}{10^\theta}$ ;  $\sigma'_\theta = \frac{\sigma_\theta^0}{10^\theta}$  are the normed values of the observation angle  $\theta_0$  and the mean square value  $\sigma_\theta$ ;

- average value of the emission factor in the form (20);
- the dispersion of the emission factor fluctuations in the form (21).

Let us now determine the correlation function  $\rho_{\varepsilon_d}(u)$  of the emission capacity  $\varepsilon_d$  of the section of the surface "eliminated" by the antenna beam and having finite dimensions by double expansion of the correlation function  $\rho_\varepsilon(u)$  determined using (26), (26'), with the function of the "eliminated" emitting area (the weighting function  $h(\mu)$ ):

$$\rho_{\varepsilon_d}(u) = \int_{-\infty}^{\infty} h(g) dg \int_{-\infty}^{\infty} h(\beta) \rho_\varepsilon(u + \beta - g) d\beta. \quad (27)$$

In the case of uniform "elimination"

$$h(\mu) = \begin{cases} \frac{1}{d} & 0 \leq \mu \leq d, \\ 0 & \text{for other } \mu, \end{cases} \quad (26)$$

where  $d$  is a linear dimension of the area around the  $ox$  axis.  
As a result, we obtain

$$R_{xx}(u) = \frac{1}{d^2} \int_{-d}^d \rho_{xx}(u-\beta)(d-|\beta|) d\beta. \quad (27')$$

Expression (27') at  $u = 0$  determines the attenuation function of the radio emission fluctuations  $X = \sqrt{R_{xx}(0)}$  characterizing the decrease in the fluctuation rate with an increase in the dimension of the "eliminated" section of the surface  $X(d)$ . The magnitude of the variations in the radio emission  $\sigma_{\sigma_d}$ , considering the dimensions of the emitting section of the surface, is determined by multiplying  $\sigma_x$ , determined by expressions (18) or (21), by the attenuation function  $X$ . Considering (14), we thus determine the variations of the antenna temperatures.

Let us determine the function  $X$  for models of a surface characterized by the correlation functions of the angles of inclination  $\rho_\theta(u)$  in the form of (11a) and 11b).

Substituting (11a) and (11b) into (26) and substituting (26) into (27), we obtain:

- when giving  $\rho_\theta(u)$  in the form of (11a)

$$X^2(d, \alpha_0) = \frac{d_0 \alpha_0 + 1}{(2\pi d_0)^2} - \frac{e^{-2d_0 \alpha_0}}{(2\pi d_0)^2} \left( \frac{2\alpha_0}{\pi} \sin 2\pi d_0 + \cos 2\pi d_0 \right), \quad (29)$$

where  $d_0 = \frac{d}{\lambda}$  is the ratio of the linear dimension of the emitting section to the average length of the sea wave  $\bar{\lambda}$ ;  $\alpha_0$  - see irregularity index included in (11a).

- giving  $\rho_\theta(u)$  in the form of (11b)

$$\chi^2(d_1) = \frac{1}{2m^2 + (\sigma'_0)^2} \left\{ 2m^2 \left[ \frac{\sqrt{x}}{d_1} \phi(\sqrt{2}d_1) - \frac{1}{d_1^2} (1 - e^{-d_1^2}) \right] + \left[ (\sigma'_0)^2 \frac{\sqrt{x}}{\sqrt{2}d_1} \phi(2d_1) - \frac{1}{2d_1^2} (1 - e^{-2d_1^2}) \right] \right\}, \quad (30)$$

where  $d_1 = \frac{d}{\sigma_0}$  is the ratio of the linear dimension of the emitting section to the magnitude of the correlation interval determined using the level of decrease in the correlation function  $\rho_0(u)$  by a factor of "e";  $\phi$  - integral of gauss probability.

We should note that expression (29) is valid at  $\theta_0 \approx 3\sigma_0$  for  $\theta_0 \geq 20^\circ$ ,  $\sigma_0 \leq 10^\circ$ , when the ratio  $\frac{2m^2}{(\sigma'_0)^2} \geq 10$ . When these conditions are satisfied, the frequency of the operating function  $\rho_2$  and correspondingly  $\chi^2(d_0, \sigma_0)$  is not doubled in the transition from  $\rho_0(u)$  to  $\rho_2(u)$ . We may show that in the case of vertical observations, the function  $\chi^2$  oscillates with a doubled frequency.

For a three dimensional surface model, in accordance with the assumption of the possible separation of variables in the expression for the correlation function of the emission capacity

$$\rho_2(u_x, u_y) = \rho_1(u_x) \rho_2(u_y)$$

, we find that the attenuation function of the fluctuations is determined in the form  $\chi = \chi_x \chi_y$ . (31)

In particular, for a surface model with  $\rho_0(u)$  in the form of (11a)

$$\chi(d_{0x}, \sigma_{0x}; d_{0y}, \sigma_{0y}) = \chi_x(d_{0x}, \sigma_{0x}) \chi_y(d_{0y}, \sigma_{0y}), \quad (31)$$

where

$$d_{0x} = \frac{d_x}{\bar{\lambda}}; \quad d_{0y} = \frac{d_y}{\bar{L}};$$

$d_x, d_y$  - linear dimensions of an area in the direction of the axes Ox and Oy;  
 $\bar{\lambda}, \bar{L}$  - the average length of a sea wave and the depth

Let us make several qualitative comments.

OF FOUR QUALITY

A change in the antenna temperature  $T_a$  with time is determined by the fact that sections with different angles of inclination to the beam all through the diagram when the surface or the emission receiver move relative to the surface.

It is apparent that this will be a maximum change when the width of the "eliminated" spot is much less than  $\lambda$  or  $(\lambda)$ , i.e.,  $\frac{d}{\lambda} \ll 1$ . In this case the observed changes in the antenna temperature are proportional to the brightness temperature of the sea  $T_b$  and its fluctuations  $\sigma_b$ . It is also apparent that with an increase in the ratio  $\frac{d}{\lambda}$  the fluctuations are smoothed. This effect is considered by the attenuation function for the fluctuations. At  $\frac{d}{\lambda} \rightarrow 0$ ;  $X=1$ ; ; at  $\frac{d}{\lambda} \rightarrow \infty$ ,  $X \rightarrow 0$ . In addition at  $\frac{d}{\lambda} = n=1,2,3..$ , the attenuation function is minimal, since a whole number of sea waves is contained in the "eliminated" spot.

A qualitative estimate shows that the magnitude of the fluctuations for horizontal polarization is two times smaller than for vertical polarization with observation angles to the horizon ranging from 15 to 60° 33

In the case of normal incidence, the fluctuations are minimal due to the smoother behavior of the reflection coefficient curves. It is also clear that at  $\psi=0^\circ$  (i.e., with the observation direction in the plane normal to the wave front) the fluctuations are maximal due to the greatest dynamic range of changes in inclination angles of the sea surface.

It can be expected that  $\bar{T}_a$  depends slightly on the ratio  $\frac{d}{\lambda}$ , since different sections of the sea surface pass through the diagram in sequence, and the time averaging is equivalent to a certain degree to averaging over the diagram.

### Calculation results

A calculation (taking into account the shading) was performed using the BESM-2 computer, and analytically using formulas (20), (21)

(29), (30).

Table 2 gives the values of the complex dielectric constants used in the calculations.

Table 2

$\lambda, \text{cm}$	0,87	1,0	1,62	3,2	6,0	10,0	30,0
$\epsilon$	11-i13	28-i36	44-i40	65-i31	76-i19	80-i20	80-i75

A portion of the calculation results is given in Figures 2-15, where regular surfaces with "three dimensional" and "two dimensional" waves are called the first and second, respectively:  $\theta_r$ - angle of inclination to the horizon;  $\varphi$ -angle in the horizontal plane between the beam and the direction of motion of the sea waves (see Fig. 1). /34

Value of  $T_a$  average over time. Figure 2 shows the values of

$\{\bar{T}_{o,A}^e / (1-\beta_{2A}) T_o\} = J_{v,A}$ , which are proportional to the brightness temperature of a surface with "three dimensional" waves and characterizing the emission capacity  $\epsilon_{v,A}$ . Similar curves are characteristic for other regular surfaces. As the calculation shows, the dependence of  $J_{v,A}$  on  $d/\lambda$  is rather slight, particularly for the angles  $\theta_r > 30^\circ$ , i.e., the width of the illuminated spot has a much greater influence upon the magnitude of the fluctuations than on the average value. Therefore the values in the figure may be used to determine not only the brightness, but also the averaged values. Here for comparison we plot the values of  $J_{v,A}$  (plane) for a plane surface, which apparently equal  $\epsilon_{v,A} = (1 - |R_{v,A}|^2)$ , where  $R_{v,A}$  is the Fresnel coefficient.

Figure 3 illustrates the angular dependence of the emission capacity calculated for a two dimensional regular model at  $\varphi = 0^\circ$ , and different values of the maximum angle of inclination of the trochoid  $\theta$  [19]. Figure 4a,b gives similar dependences determined for stochastic models, three dimensional and two dimensional, at  $\varphi = 0^\circ$  and for different values of the sea parameter  $\sigma_0$ . The ordinate axis shows

the emission capacities, and the values of the polarization coefficients  
 $\rho = \frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}$  which are derivatives of them.

Figure 2

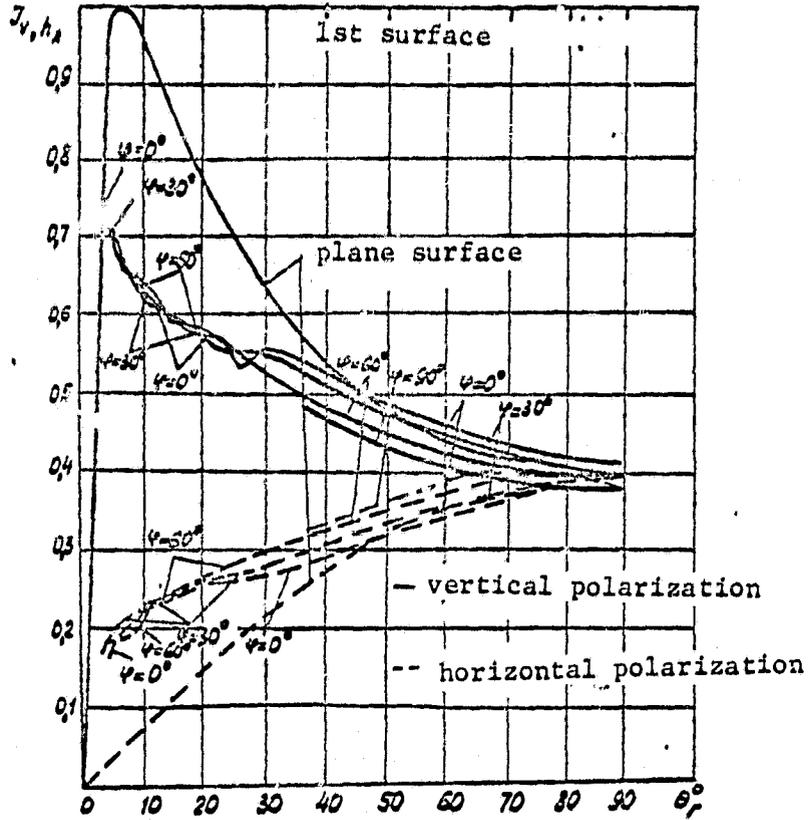


Figure 3

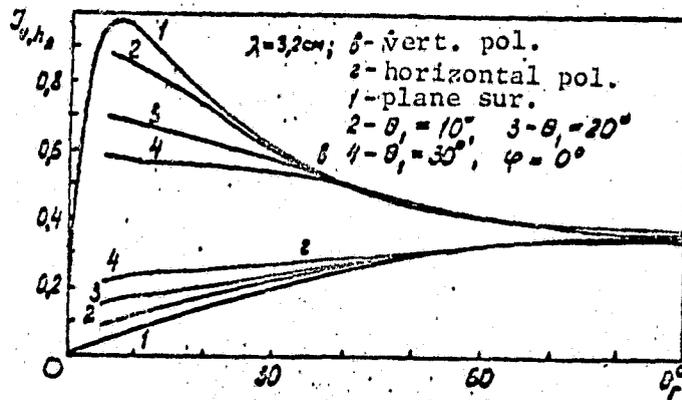
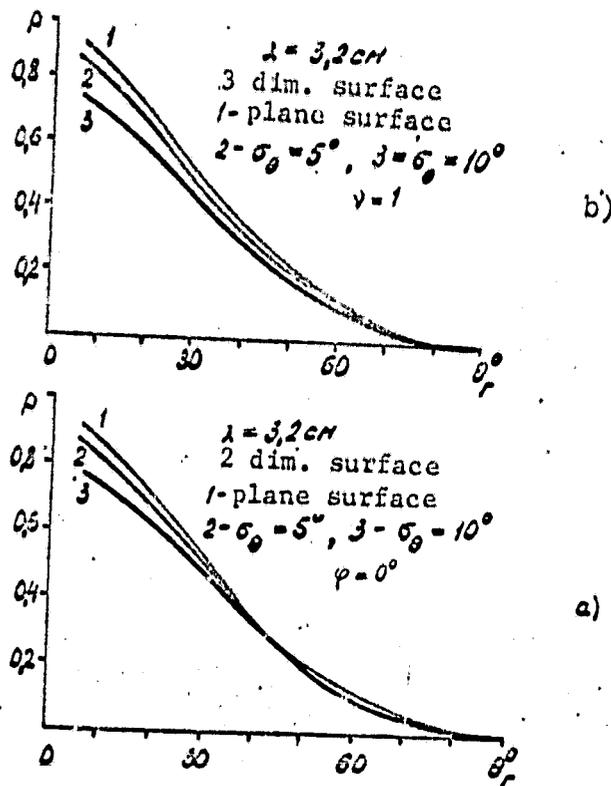


Figure 4



As follows from the calculations, for three dimensional models, regular and stochastic, the azimuthal dependence of the emission capacity and degree of polarization are either expressed weakly or not at all (isotropic model). For two dimensional models this dependence holds and is manifested in an increase in the emission capacity for vertical polarization, and a decrease for horizontal polarization which with a change in the azimuthal angle  $\varphi$  from 0 to 90% [19,20].

Figure 5 shows the spectral dependence of radio brightness determined using (20) at  $\varphi = 0^\circ$ ,  $\theta_0 = 0^\circ$  and  $\sigma_0 = 15^\circ$ . In the analytical calculations the values of the coefficients  $A_{\beta,2}$  used are given in Table 3.

Table 3

$\lambda, \text{cm}$	0,87	1,0	1,62	3,2	6,0	10,0	30,0
$A_p \cdot 10^5$							
$1/2\rho\sigma^2$	6,7	6,6	6,5	6,5	6,5	6,3	5,9
$A_p \cdot 10^5$							
$1/2\rho\sigma^2$	6,7	5,0	4,7	4,6	4,3	4,3	3,7

Fluctuations of the radio emission of the sea. Figures 6-8 show the values of the brightness temperature fluctuations of the sea radial emission  $\delta T_s = \sqrt{(\overline{T_s - \bar{T}_s})^2}$

as a function of the observation angle for different values and different types of regular surfaces; Figures 9-12 - for stochastic models, and Figures 13-15 - values of the attenuation function of the fluctuations  $X$  (we recall that the fluctuations for a given  $d/\lambda$  are determined by the product  $\delta T_s \cdot X(d/\lambda)$  ).

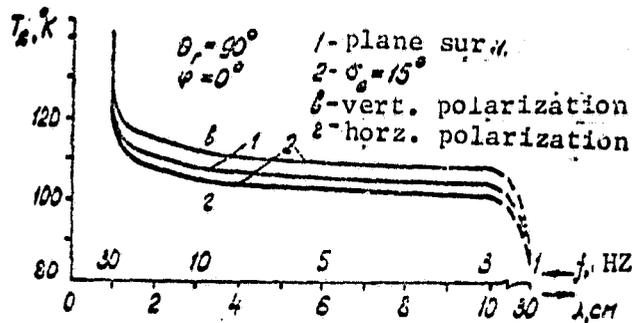
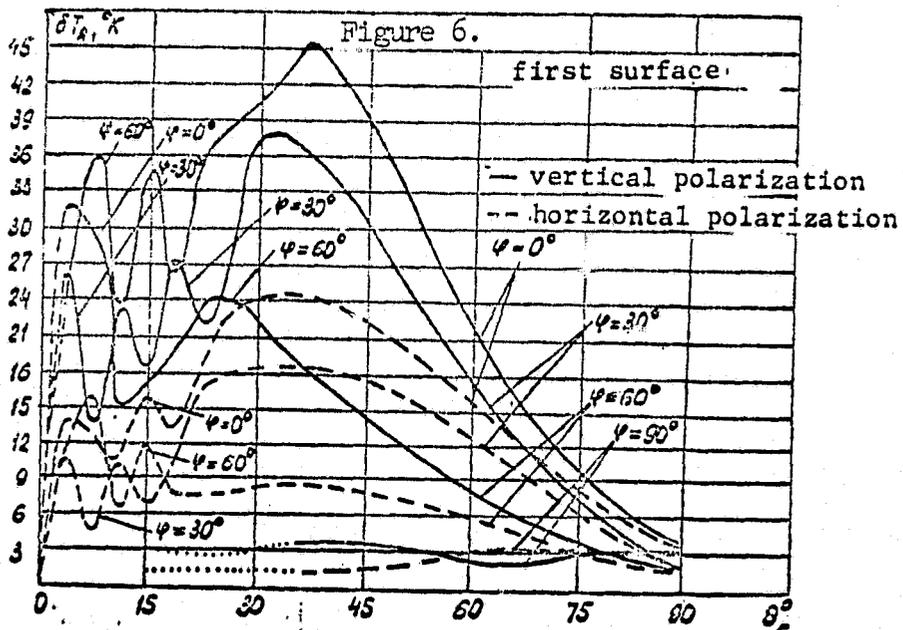


Figure 5



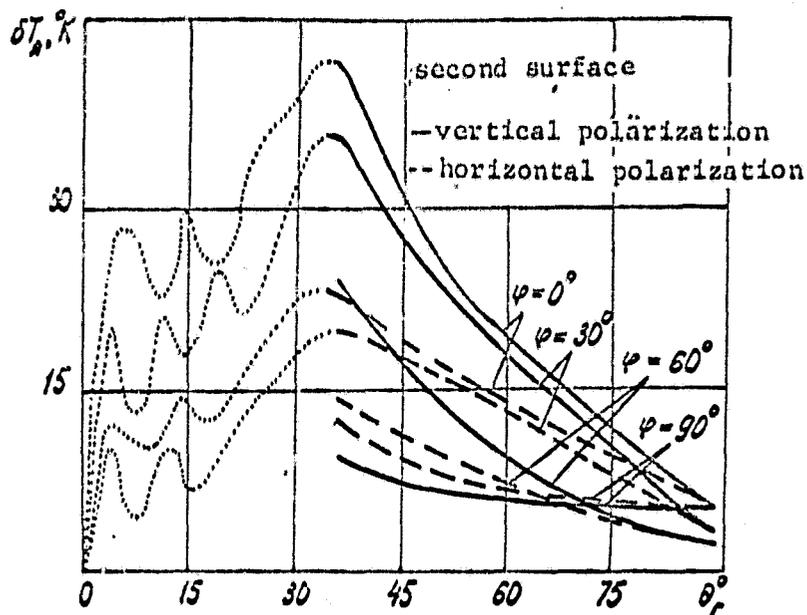


Figure 7

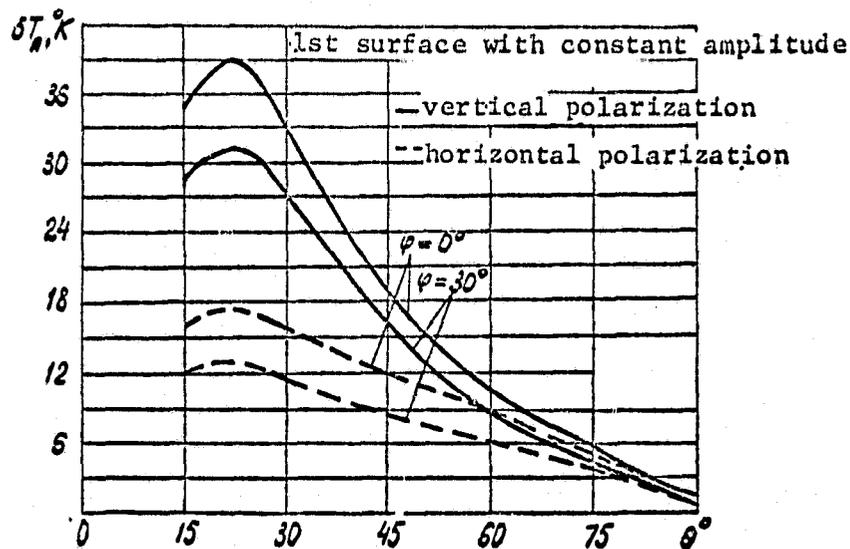


Figure 8

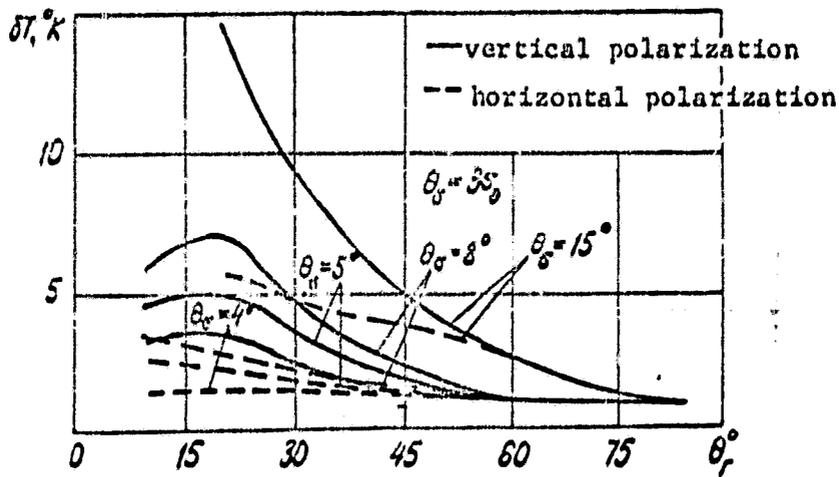


Figure 9

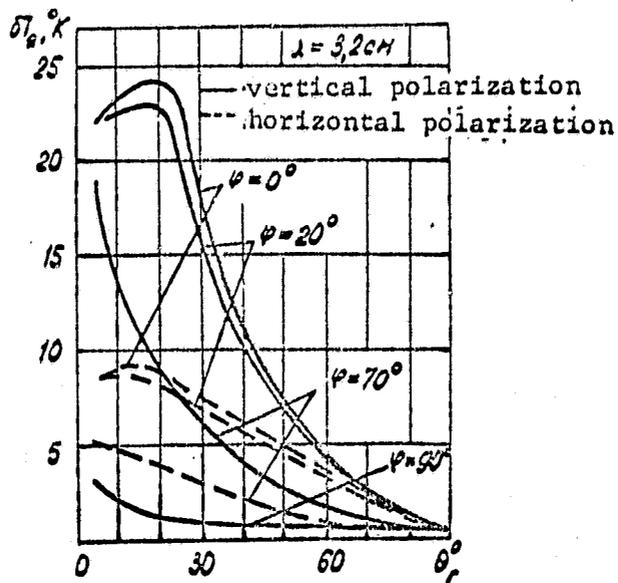


Figure 10

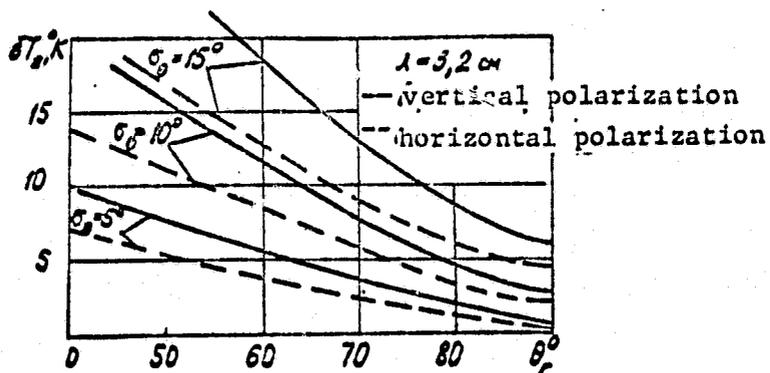


Figure 11

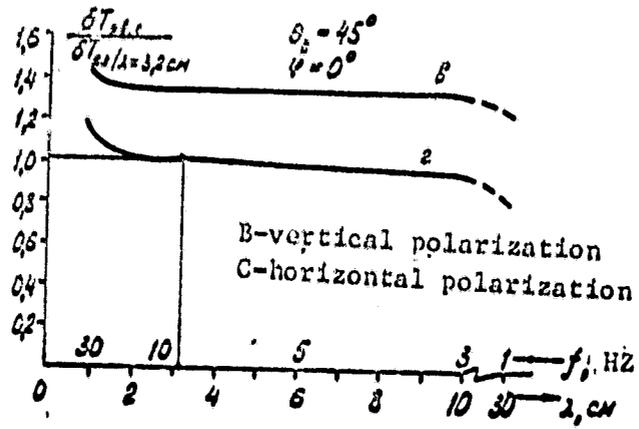


Figure 12

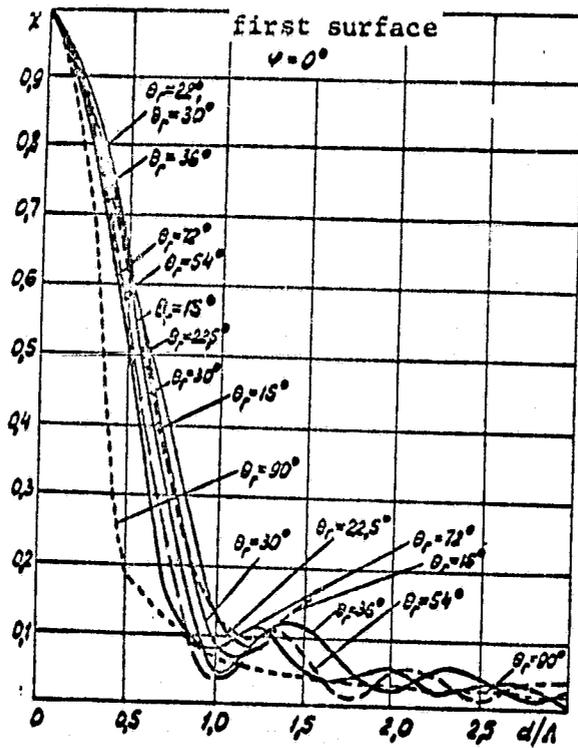


Figure 13

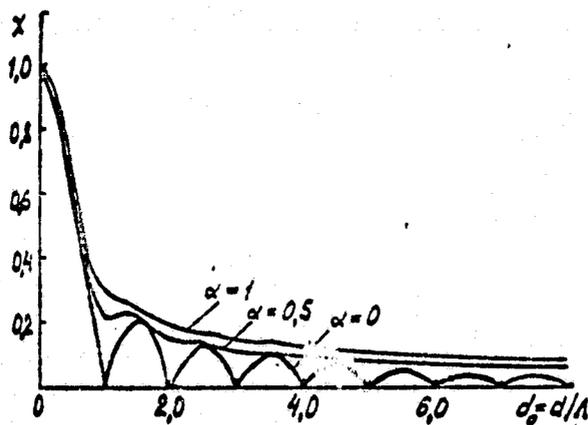


Figure 14

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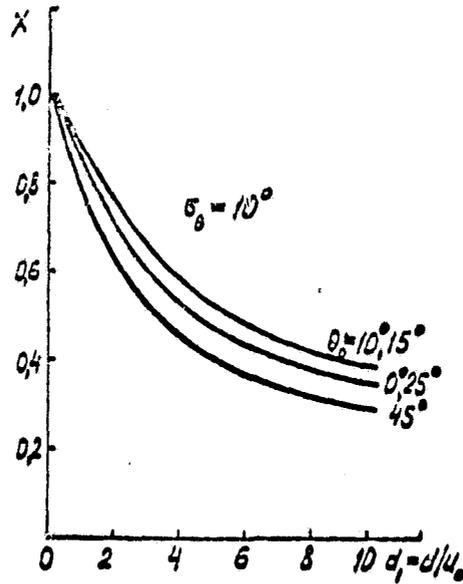


Figure 15

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It follows from the calculations that the maximum fluctuations in the emission from a regular moving sea surface occur at  $\varphi = 0^\circ$ , i.e., in an observation direction which is normal to the front of the sea wave, and at angles of inclination toward the horizon which are close to the maximum angle of inclination of the sea surface, which is physically obvious, since at  $\varphi = 0^\circ$  there is a maximum of the dynamic range of the angles of the sea surface passing through the diagram. For small observation angles (under shading conditions) there are maximums and minimums  $\delta T$ . The magnitude of the fluctuations for horizontal polarization is approximately two times smaller than for vertical polarization for observation angles with the horizons from approximately 15 to  $60^\circ$ . The maximum magnitude of fluctuations at  $\varphi = 0^\circ$  occur for vertical polarization of  $40-45^\circ\text{K}$  and for horizontal polarization -  $20-25^\circ\text{K}$ . When the direction of observation is along the wave front ( $\varphi = 90^\circ$ ), the fluctuations of the brightness temperature are minimum and are  $5-10^\circ\text{K}$ .

Figures 9-11 show fluctuations of radio emission determined for stochastic models of the sea surface with non-uniformities which are close to the lengths of the electromagnetic waves. The graphs in

Figures 9 and 10 were calculated on a computer using formula (18).  
The graphs in Figure 11 - using formula (21).

It follows from the graphs in Figures 9 and 10 that, in the case of regular models, the fluctuations of radio emission at angles of  $\theta_r < 45+50^\circ$  for horizontal polarization are two times smaller than for vertical polarization.

For a maximum angle of inclination  $\theta_e = 10+15^\circ$  ( $\theta_e = 3\sigma_e$ ), i.e., for values of the parameter  $\sigma_e = 3+5^\circ$ , the maximum fluctuations may be  $10-15^\circ$  for an observation angle of  $\theta_r = 20^\circ$  at  $\theta_r > 30^\circ$  the magnitude of fluctuation does not exceed  $10^\circ\text{K}$  and at  $\theta_r > 45^\circ$  the fluctuations are smaller than  $5^\circ\text{K}$ .

For a two dimensional stochastic model, just as for a regular model, there is a characteristic azimuthal dependence of the fluctuation intensity.

Figure 12 shows the spectral dependence of the radio emission fluctuation intensity determined using formula (24) for a two dimensional model at  $\varphi = 0^\circ$ . The values of the fluctuation intensity are normalized with respect to  $\sigma_e$  at a wave length of  $\lambda = 3.2$  cm for horizontal polarization.

When the illuminated spot is much larger than the length of the sea wave, the fluctuations of the sea are greatly attenuated. It can be seen from Figure 13, which characterizes the fluctuation attenuation function for a three dimensional regular model at  $\varphi = 0^\circ$  \* it may be seen that at  $d/\lambda \geq 1$  the fluctuations are attenuated by approximately a factor of 10, and at  $d/\lambda \geq 2$  - by a factor of 20. At  $d/\lambda = 0.5$  we may expect a decrease in the fluctuations by a factor of 2, and even a factor of 3-5 when observing a "three dimensional" wave vertically below ( $\theta_r = 90^\circ$ ).

\* As the calculations show, similar curves  $\chi(d/\lambda)$  are characteristic for other regular surfaces and for the values  $\varphi = 30, 60, 90^\circ$ .

Figures 14 and 15 give graphs of the fluctuation attenuations for a two dimension stochastic model at  $\varphi = 0^\circ$ . Figure 14 illustrates the dependence  $X(\alpha_0)$ , calculated using (29) for different values of the index for sea irregularity  $\alpha_0$ . As follows from the results, with an increase in the sea regularity, when the values of  $\alpha_0$  decrease, there is a decrease in the corresponding values of  $X$ . The curve for  $\alpha_0 = 0$  characterizes the limiting case for a regular two dimensional sea. /46

Figure 15 gives graphs of the function  $X(d_1)$ , determined using (30) for different values of the observation angle.

In conclusion we should note that when calculating sea emission considering the atmospheric emission reflection from the sea surface, as  $|R|^2$  we may use  $(1 - \mathcal{J}_{\nu, h_s})$ , where  $\mathcal{J}_{\nu, h_s}$  is given in Figure 2.

Figures 16-20 give some of the measured values for the sea radio emission fluctuations at centimeter wave lengths. Figures 16-18 also show the theoretical values of the fluctuations calculated for models of the sea surface; I - three dimensional; II - two dimensional; III - three dimensional waves with half amplitude, and Figures 19 and 20 give the values determined for stochastic models. When determining the theoretical values of  $\sqrt{\delta T_r^2}$  we use the values  $\delta T_r$  for a given angle of inclination  $\theta_r$  shown in figure 5-9, and the calculated value for a given  $\varphi$  and  $d/\Lambda$ . The quantity  $\Lambda$  is determined by points and by direct measurements, and the quantity  $d$  is calculated using the well known quantities  $\theta_r$ ,  $H$  and  $\delta \theta$  - the half width of the main directional diagram blade using the formula  $d = r \delta \theta / \sin \theta = H \delta \theta / \sin^2 \theta$ . where  $r$  is the distance from the antenna to the sea surface in the direction of the main blade.

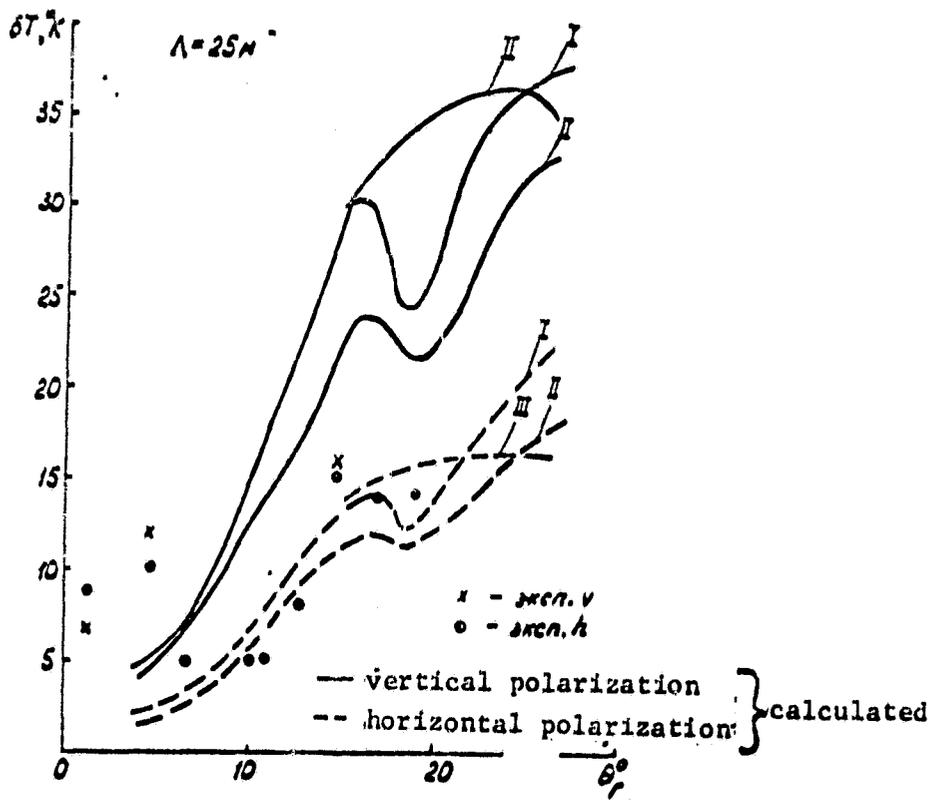


Figure 16

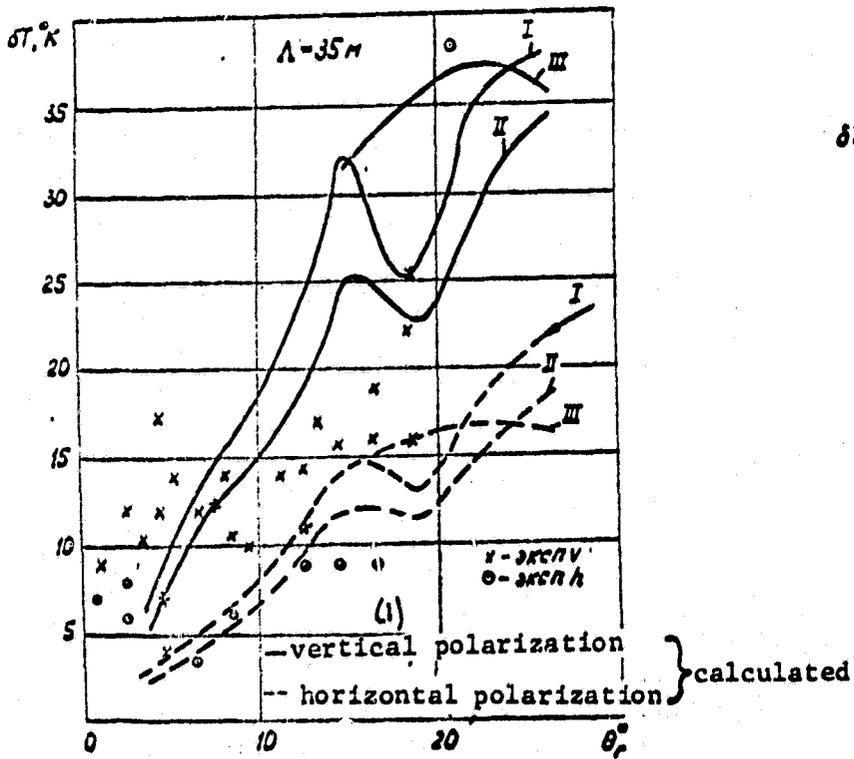


Figure 17

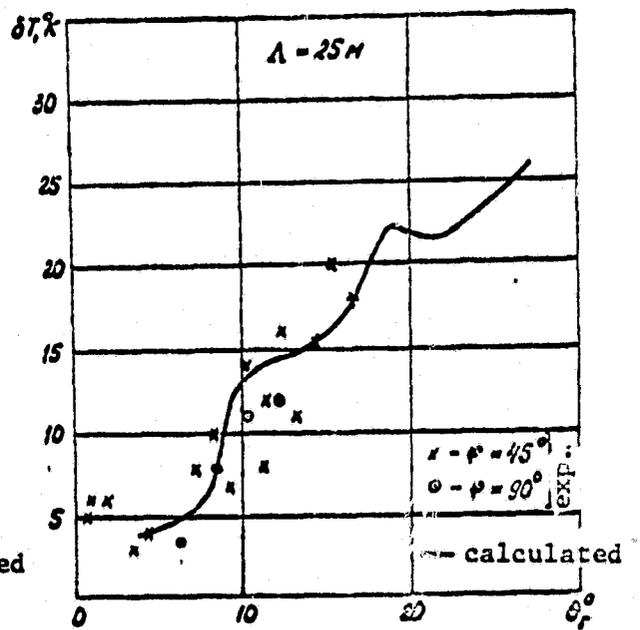


Figure 18

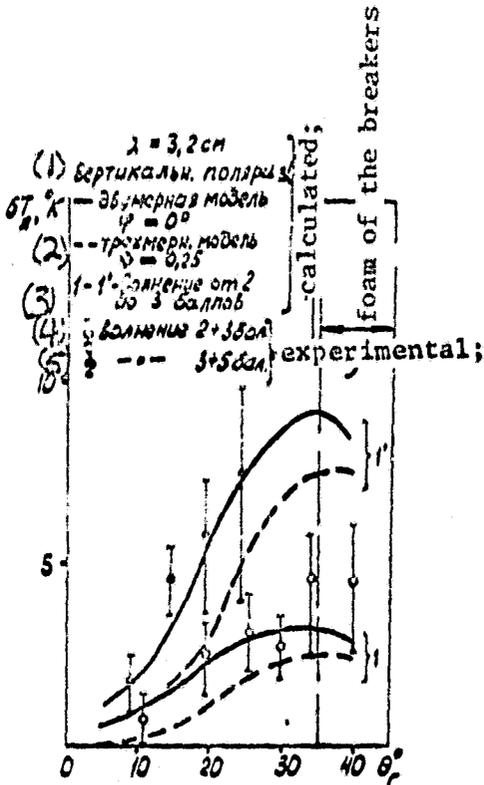


Figure 19

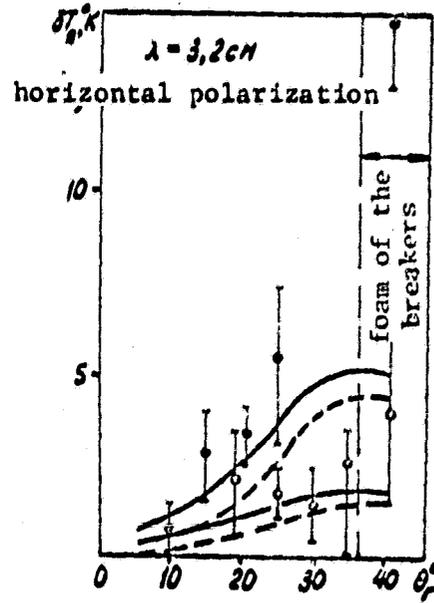


Figure 20

- Key
- 1-vertical polarization two dim. model
  - 2-three dimensional model;
  - 3-swell from 2 to 3 points;
  - 4-swell, 2-3 points;
  - 5-3-5 points;

The data obtained in Figures 19 and 20 were obtained for a /50 change in the sea from 0 to 5 points. A range of observation angles  $0 < \theta_r < 50^\circ$ . corresponds to the sea surface. For strong agitation of about 4-5 points, this range is reduced, since the values of  $30 < \theta_r < 50^\circ$  correspond to the sighting of surface sections covered by foam. As the measurements showed, foam entering the beam leads to

to an increase in the fluctuations in the average radio emission intensity. Since the foam and the froth formed from the drops of water and air bubbles closely agree with the surrounding space, i.e., the reflection coefficients for them are close to zero, they are sources of intense emission similar to the emission of an "absolutely black" body. Based on the measurement data, the emission capacity of the foam reaches values of 0.9.

An examination of Figures 16-20 shows that the experimental data closely coincide with the calculated data. This confirms the validity of the theory and the idealizations selected and can serve as a basis for using the computational results for determining the expected radio emission fluctuation.

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