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ON ANGULAR DISTRIBUTION OF RADIATION REFLECTED FROM A RUFFLED SEA

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ABSTRACT

A mathematical model has been developed for describing the angular distribution of monochromatic electromagnetic radiation reflected from the ruffled sea surface. The reflectivity of the sea is calculated in view of the possibility of a thin oil film on the water. The model works both in case of an incident parallel beam radiation as well as in case of diffuse and direct solar radiation.

The model may become of practical use for the interpretation and analysis of measuring results of upwelling radiation above the sea surface (to estimate the relative contribution of the sun glitter and directly reflected sky radiation to the results of the measured sea brightness , to find the optimum directions of observations for determining the zones with increased or reduced sea radiance etc.).

The upwelling solar radiance above the sea surface consists of two components: 1) the sun and sky radiation directly reflected from water surface 2) solar radiation diffusely backscattered by seawater . An extensive and profound investigation on the radiance distribution over a ruffled sea has been made by G.N. Plass with co-authors using the Monte Carlo method (Plass et al. 1975, 1976, 1977, 1981, Guinn et al. 1979) . However, we need a simple mathematical model describing the field of upwelling radiance above the sea in order to analyze and verify our experimental results (measurings have been carried out on board of a research vessel or helicopter). The computer of the research vessel must be able to realize the program of the mathematical model.

As a first step, a simple mathematical model for calculating the electromagnetic radiation directly reflected from the sea surface is developed. The model works both in case of an incident parallel beam radiation as well as in case of the diffuse and direct solar radiation. It describes reflected radiance measured by fictitious receiver as a function of the zenith angle (ϑ_m) and azimuth (α_m) of observation. The distorting influence of the atmosphere between the receiver and reflective surface is not taken into account. Nevertheless, in cases of small distances between the receiver and sea surface (vessel, helicopter) estimations made by this model could be satisfactory enough.

It is known that the reflected component of solar radiation B_R:

$$B_R(\alpha_m, \vartheta_m) = B(\alpha, \vartheta) R(\varphi_{nm}, x_0, x_1 \dots x_i), \tag{1}$$

where $B(\alpha, \vartheta)$ -sky brightness in the direction of ϑ (zenith angle) and α (azimuth), R -reflectivity of a surface element of the wind-ruffled sea, φ_{nm} -angle between the normal of wave surface element and the direction of incident beam, $x_0, x_1 \dots x_i$ -parameters characterizing optical properties of the sea surface under consideration.

Due to the dynamic character of the wind-ruffled sea, the determination of the unique value of the radiation reflected from a fixed surface element of water is quite out of question. Unregularity of real waves necessitate to use the probability functions to characterize the process of reflection from the rough sea surface. The reflected component of upward radiance is considered a weighted average, the probability of reflection from a given solid angle being a weight ratio. The reflecting wave surface is described by the probability law providing us the distribution of the normals of wave surface elements. Hence, we have

$$dB_R = B(\alpha, \vartheta) R(\varphi_{nm}, x_0, x_1 \dots x_i) P(\alpha_n, \vartheta_n) d\omega^*, \tag{2}$$

where $$d\omega^* = \frac{d\omega}{4\cos\varphi_{nm}} = \frac{\sin\vartheta \, d\vartheta \, d\alpha}{4\cos\varphi_{nm}}. \tag{3}$$

Here α_n and ϑ_n -correspondingly the azimuth and zenith angle of the normal of wave surface element, $P(\alpha_n, \vartheta_n)$ -the function characterizing the probability of direction of this normal, $2\varphi_{nm}$ - angle between the direction of observation (α_m, ϑ_m) and the variable direction (α, ϑ), $d\omega$ -solid angle of the sky surface element corresponding to the incident radiance $B(\alpha, \vartheta)$, $d\omega^*$ -solid angle for the direction of normal (α_n, ϑ_n) corresponding to the solid angle of incident radiation $d\omega$.

An incident beam could be both the direct solar and sky radiation. Hence,

$$B(\alpha, \vartheta) = B_0(\alpha_0, \vartheta_0) + B_S(\alpha, \vartheta), \tag{4}$$

where $B_S(\alpha, \vartheta)$ -brightness of the sky, $B_0(\alpha_0, \vartheta_0)$-brightness of the visible Sun's disc, α_0 and ϑ_0 -correspondingly the azimuth and zenith angle of the centre of Sun's disc. However, it's better to use not B_0, but the value of direct solar radiation flux onto a horizontal surface (E_0), which data is more available. As it is known, approximately

$$B_0 \approx \frac{E_0}{\cos\vartheta_0 \, \omega_0}, \tag{5}$$

where ω_0 -solid angle of the visible Sun's disc.

Taking into account the various directions of wave surface normals, we obtain

$$\bar{B}_R = \int_0^{2\pi}\int_0^{\pi/2} B_S(\alpha, \vartheta) R(\varphi_{nm}, x_0, x_1 \dots x_i) P(\alpha_n, \vartheta_n) \frac{\sin\vartheta}{4\cos\varphi_{nm}} d\vartheta d\alpha + \frac{E_0 R(\varphi_{mn0}, x_0 \dots x_i) P(\alpha_{n0}, \vartheta_{n0})}{4\cos\vartheta_0 \cos\varphi_{nm0}}. \tag{6}$$

Here $2\varphi_{nmo}$ -angle between the directions of observation and the sun, α_{no} and ϑ_{no} - correspondingly the azimuth and zenith angle of the normal of sea surface element in case of the incident direct solar radiation. Both α_n and ϑ_n are calculated as the azimuth and zenith angle of the bisectrix of the angle between the directions of (α_m, ϑ_m) and (α, ϑ). In case of the direct radiation , α_{no} and ϑ_{no} are calculated for the bisectrix of the angle between (α_m, ϑ_m) and (α_o, ϑ_o).

The first term of the formula (6) describes the reflected sky radiance, the second the sun glitter.

Evidently the data on B_s as a function of α and ϑ for various Sun's locations is needed. Practically, in most cases, we have the experimental results of total solar and sky irradiance, but not the angular distribution of $B_s(\alpha, \vartheta)$. For the first approximation we took the sky radiance as subjected to the following assumptions: 1) the maximum value of B_s corresponds to the direction of the visible Sun's disc: 2) the sky radiance decreases continuously with the direction (α, ϑ) moving away from the sun's direction. Under these restrictions the angular distribution of $B_s(\alpha, \vartheta)$ can be described mathematically by an ellipsoid assuming the longer axis of symmetry directed straight to the Sun's disc. For our model such a function $B_s(\alpha, \vartheta)$ was determined for absolutely clear (for various sun's heights) and completely cloudy sky. It must be pointed out that one way to improve our mathematical model is to obtain more perfect description of $B_s(\alpha, \vartheta)$.

The values of reflectivity $R(\varphi_{nm}, x_o \ldots)$ both for the cases of pure water and a thin oil film on the sea surface are computed by the formulae presented by Arst, Kard (1981) while using the optical constants of water and oil taken from the investigations of Irvine, Pollack (1968) and Zolotariev et al. (1977).

For determining the function $P(\alpha_n, \vartheta_n)$, the results of the investigation by Guinn et al. (1979) are very convenient: on the basis of the data of Cox and Munk (1954) they have presented the formulae for calculations of $P(\alpha_n, \vartheta_n)$ as well as the necessary expressions for computational parameters (both for pure water and oil slick). The expressions are developed in the form that depends only on the velocity and direction of the wind. Those characteristics are easily available. We have used these formulae for computing the values of $P(\alpha_n, \vartheta_n)$ and $P(\alpha_{no}, \vartheta_{no})$.

The given model is realized as a program for a computer. The initial data is: 1) wavelength of incident radiation; 2) solar zenith angle and azimuth; 3) zenith angle of observation (the azimuth of observation is considered to be zero); 4) thickness of oil film; 5) optical constants of water and oil; 6) wind velocity and direction; 7) downwelling total and direct solar irradiance measured on the sea surface. (It is possible to refine the results, having some measured values of sky brightness as initial data that help to determine the function $B_s(\alpha, \vartheta)$ for the case under consideration). The results of the program's single run are the values of the upwelling reflected radiance, separately for the reflected sky radiation and sun glitter (both for the calm and ruffled sea with and without oil film covering).

The model may become of practical use for the analysis of measuring results of upward radiation above the sea. One of the possible applications can be the estimation of relative contribution of the sun glitter to the results of the measured sea radiance. Besides, the model enables to establish the optima directions of observation in determining the zones with increased or reduced (compared to the surrounding sea surface) sea radiance for the given observation conditions (the Sun's position, wind velocity and direction, cloudiness). The above zones of different (increased or reduced) brightness may result from the oil film , variation of sea roughness under the influence of internal waves etc.

We have carried out the computations by the given model for the incident solar radiation wavelength of 0.7 microns .It must be marked that for the wavelengths approximately 0.7 microns and more the diffusely backscattered (from water) component of upward radiation is negligible. Hence, for these wavelengths the reflecting component represents practically the sea brightness.

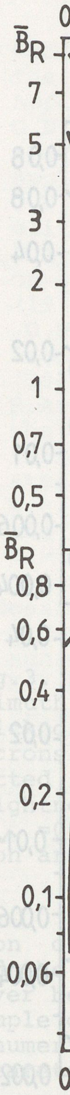
In the calculations the relationship between the sea brightness and the observation conditions (the observation direction, the solar zenith angle and azimuth, the wind velocity and direction) is considered.

Since we had no initial data of total and direct solar radiation for all cases under consideration and no data at all to determine the B_s as a function of α and ϑ ,we used the averaged data for the values of the relationship between the direct and total solar radiation as well as for the values of the angular distribution of sky brightness taken from handbooks (see Kondratiev (1954),Ivanoff (1978),Avaste et al.(1962)). By means of these materials the relative values of B_s and E_o were determined and also the parameters of the ellipsoid describing the angular distribution of $B_s(\alpha, \vartheta)$.As a result, we have by now the values of $\bar{B}_R$ only in relative units.

Some examples of our results are demonstrated below. Fig.1 and 2 represent the variability of sea brightness according to the change of the solar zenith angle (ϑ_o) and the wind velocity (w) (both for pure and for oil slick covered water). A significant difference in results of $\bar{B}_R$ is observed. One can see that in certain conditions anomalous contrasts may appear - brightness of clear water exceeds the corresponding values of the system "oil film-water". Fig.3 enables to estimate the contribution of sun glitter to the sea brightness. As seen, the maximum values of glitter occur for solar azimuth angles being approximately 180^0 and apparently the opposite direction is more recommended for measurements where the influence of sun glitter must be minimized. It is established too that for avoiding the influence of sun glitter, the nadir direction of measurements is not suitable, but the directions of ϑ_m being about $40 \div 50^o$ must be preferred (the same conclusion is presented in the papers of Plass et al.(1977)).

In Fig.4 we can see the scanning curves of $\bar{B}_R$(zenith angle ϑ_m changing from 20^o to 50^o) with the assumption that in the zone of ϑ_m from 26^o to 34^o the water is covered with oil slick. We found that the shapes of the brightness curves as well as the contrasts between the values of $\bar{B}_R$ with and without oil film on water depend significanly on the solar azimuth angle.

Our results show likewise the dependence of $\bar{B}_R$ on the wind direction. It means that in spite of the stochastic character of the sea roughness the certain slopes of waves dominate. This dependence is not so strong for oil-covered sea: hence, the waves are more symmetrical under these conditions.



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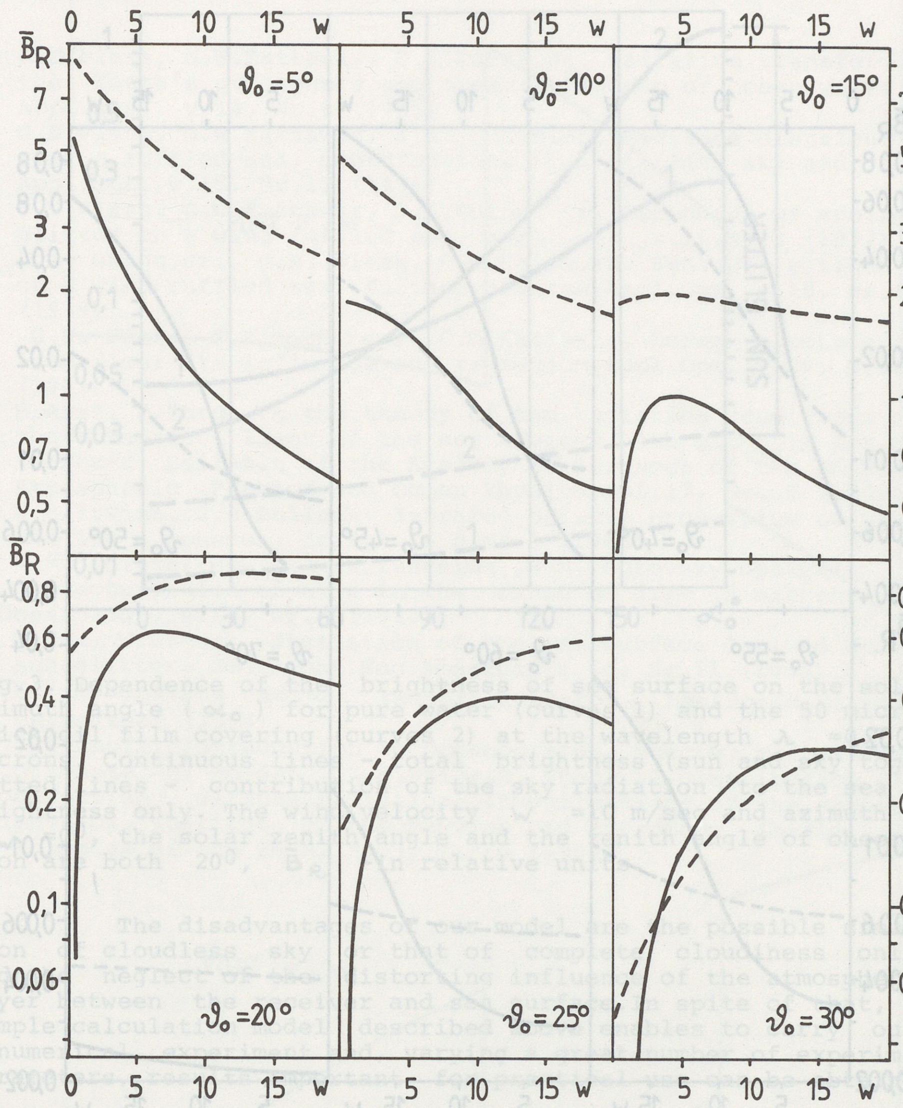

Fig.1. Dependence of the brightness of sea surface on the solar zenith angle (ϑ_o) and on the wind velocity (w) for the zenith angle of the observation $\vartheta_m = 0$ and at wavelength $\lambda = 0.7$ microns. Continuous lines - for pure water, dotted lines - for 50 microns thick oil film on the water. The wind and solar azimuth angles are equal. The $\bar{B}_R$ values are in relative units, the w values in m/sec.

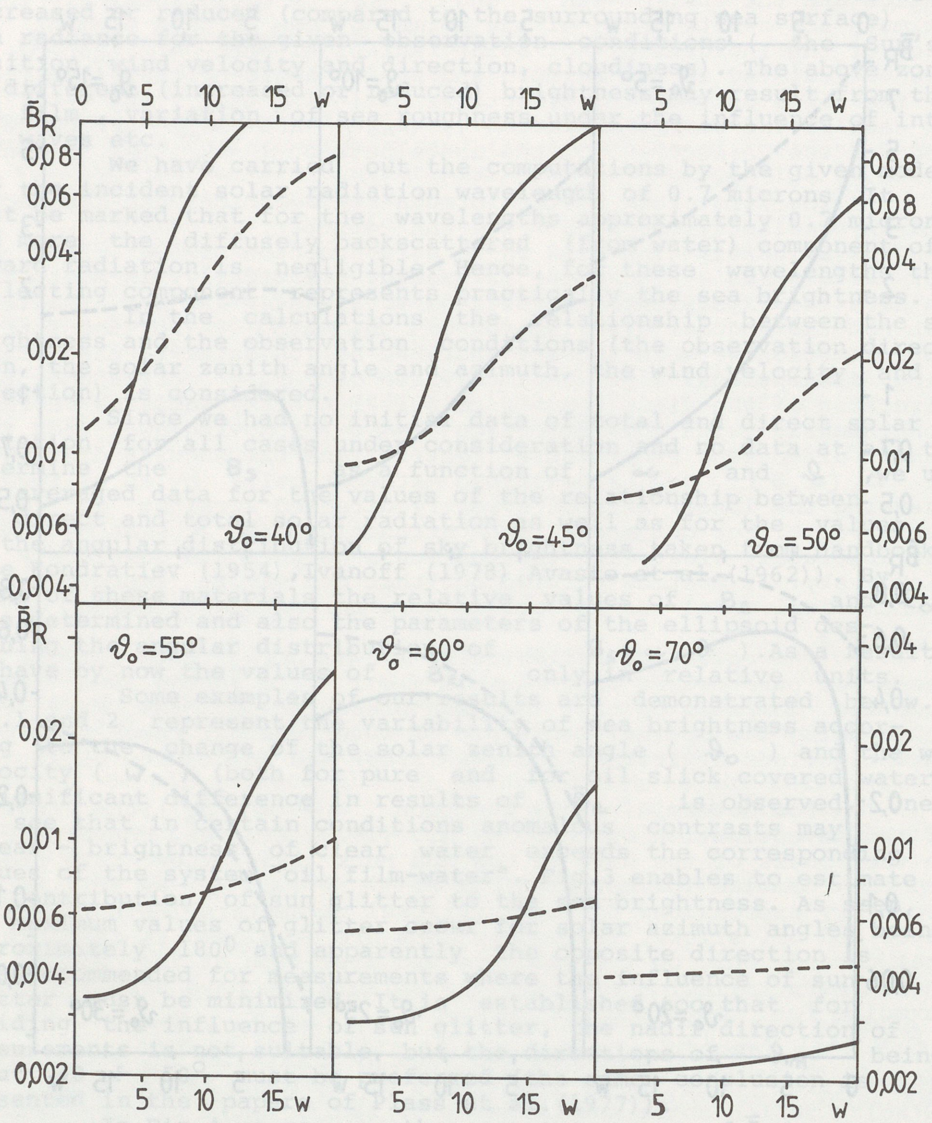

Fig.2. Dependence of the brightness of sea surface on the solar zenith angle and on the wind velocity for ϑ_m =0 and λ =0.7 microns. The symbols and units are the same as in Fig.1.

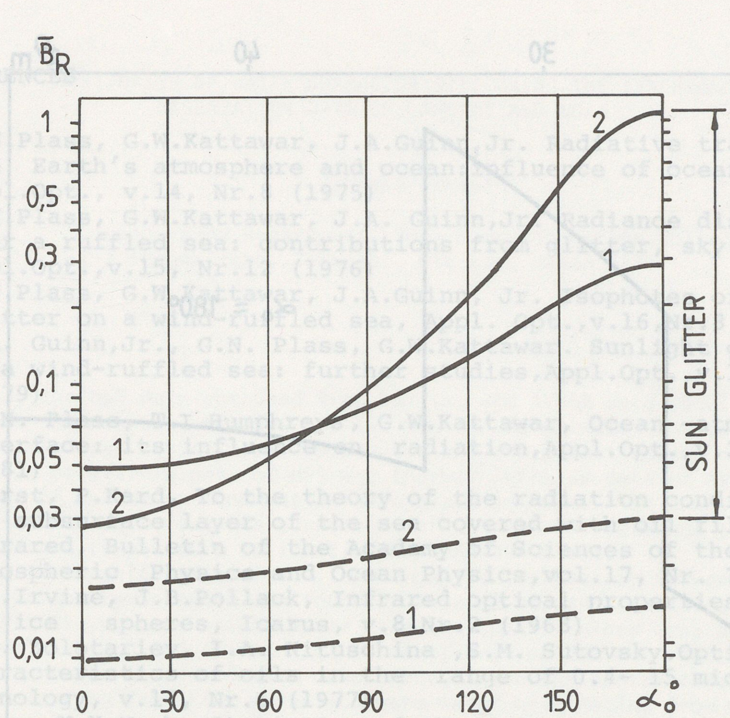

Fig.3. Dependence of the brightness of sea surface on the solar azimuth angle (α_o) for pure water (curves 1) and the 50 microns thick oil film covering (curves 2) at the wavelength λ =0.7 microns. Continuous lines total brightness (sun and sky together), dotted lines contribution of the sky radiation to the sea brightness only. The wind velocity w =10 m/sec and azimuth α_w =0^0, the solar zenith angle and the zenith angle of observation are both 20^0, $\bar{B}_R$ -in relative units.

The disadvantages of our model are the possible simulation of cloudless sky or that of complete cloudiness only and the neglect of the distorting influence of the atmospheric layer between the receiver and sea surface.In spite of that, the simple calculation model described above enables to carry out a numerical experiment and, varying a great number of experimental parameters, results important for practical use can be obtained.

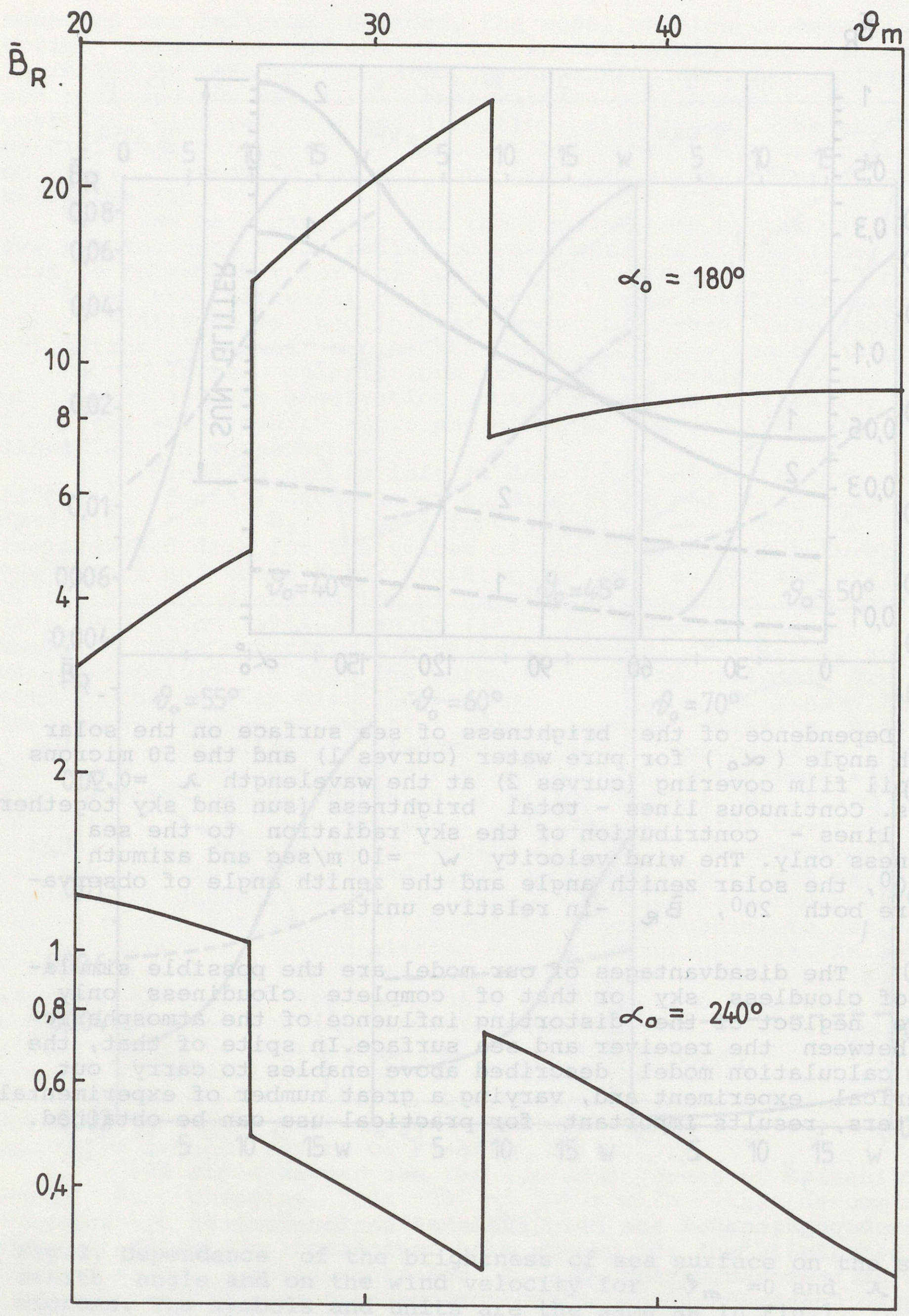

Fig.4. Dependence of the brightness of the sea surface on the zenith angle of observation (ϑ_m) at λ =0.7 microns assuming that only in the zone of $24^0 \leq \vartheta_m \leq 36^0$ the water is covered with 50 microns thick oil film. The solar azimuth angle is shown near both curves. The wind velocity w =10 m/sec and azimuth α_w =90^0, $\bar{B}_R$ - in relative units.

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ABSTRACT

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