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Bragg Scattering of Centimeter Electromagnetic Radiation from the Sea Surface: The Effect of Waves Longer Than Bragg Components

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Abstract—The effect of sea surface waves longer than Bragg components on the backscattering of centimeter electromagnetic radiation is studied on the basis of data on direct field measurements of sea-surface slopes. A situation in which waves with wavelengths greater than 10 cm are longer than the Bragg components is considered. The increase in the backscattering cross section that is due to the presence of long waves is numerically estimated for sounding at horizontal and vertical polarization. Nonlinear effects in the field of surface waves result in the departure of the distribution of sea-surface slopes from a Gaussian distribution and lead to a change in the backscattering cross section. At a sounding angle of 35°, this change may reach 15% with respect to the cross section calculated for a Gaussian surface.

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INTRODUCTION

Studies of radio-wave scattering from the sea surface were initiated in the early 1950s [1]. However, despite its long history, the problem of wave scattering from the sea surface remains to be solved completely; this is mainly due to the fact that the field of sea surface waves has not been studied sufficiently [2, 3].

The major scatterers of radio radiation during remote sensing of the sea surface from space vehicles are short surface waves. The dependence of the energy of short surface waves on the wind velocity forms the basis for its determination by means of remote sensing [4]. The method proposed in 1966 for determining the wind velocity with the aid of instruments recording radio-wave scattering on the ocean–atmosphere boundary is presently the only way to obtain global-scale information on the near-water wind [5].

The presence of long waves, the energy of which is less correlated with wind velocity than the energy of short waves, is a source of errors during scatterometric measurements of the near-water wind velocity [6]. Long waves alter the local slope of the sea surface (the geometric effect) and modulate the energy of Bragg components (the dynamic effect). In order to describe the effect of long waves on radio-wave scattering from the sea surface, using the linear modulation transfer function was proposed in [7]. This study is restricted to an analysis of the geometric effect.

Variations in local sea-surface slopes produce not only major energy-carrying (dominant) waves but also shorter waves that are, however, longer than Bragg components. In order to take this factor into account, the backscattering cross section is expanded in a power series of local angle of sea-surface slopes and the subsequent averaging over their distribution function is used [8, 9]. In the absence of data on the actual variability of statistical characteristics of sea-surface slopes, the drawback of this approach is the complexity of assessing the convergence of the series.

In analyzing the geometric effects that are caused by the presence of long waves, the central problem is describing the distribution of sea-surface slopes. Different models are commonly used for this purpose in the absence of detailed information on statistical characteristics of the sea surface [9, 10]. These models are constructed for the spectrum of surface waves on the basis of solving the kinetic equation [2] or numerical models of the sea-surface relief [10]. The relatively small amount of experimental data on sea-surface slopes has caused the Gaussian model to be used as an approximation to the present day [11–13]. This model is constructed under the assumption that, in a spatially homogeneous wave field, all of its components are independent and their phases are distributed randomly and uniformly.

The aim of this study is to analyze the effect of long (compared to Bragg components) surface waves on the Bragg scattering of radio waves in the backward direction on the basis of the data of in situ measurements of sea-surface slopes.

BRAGG SCATTERING OF RADIO WAVES FROM THE SEA SURFACE

At angles of incidence greater than 20° to 25°, radio-wave scattering from the sea surface has a resonance character and is described using the method of small perturbations [14]. In the zero-order approximation, where resonance (Bragg) components of the surface-wave field propagate over a plane surface, the backscattering cross section may be written as

$$\sigma_p^0(K, \theta, \alpha) = 8K^4|G_p(\theta)|^2\Xi(\mathbf{k}_B), \tag{1}$$

where θ is the angle of incidence; α is the azimuthal angle; G_p is a function of sounding angle, which is determined by the form of polarization p; and Ξ is the spectrum of the sea surface height. The resonance condition, which relates the wave numbers of surface waves k_B and backscattered electromagnetic waves K, has the form

$$\mathbf{k}_B = K2\sin\theta. \tag{2}$$

Bragg scattering is produced by components propagating in the sounding direction, i.e., having the azimuthal angle φ_B, which satisfies the relation

$$\varphi_B = \alpha, \quad \text{or} \quad \varphi_B = \alpha + \pi. \tag{3}$$

In the following, waves with wavelengths greater than the wavelength of Bragg components will be considered long. The presence of the long waves results in the Bragg components propagating over a curved surface. This in turn leads to a change in the local angle of incidence of radio waves. As a consequence, the value of the function of sounding angle $G_p = G_p(\theta - \beta_\uparrow)$ changes, and the wave number of the Bragg component becomes a function of three variables: $\mathbf{k}_B = (K, \theta, \beta_\uparrow)$. Thus, in the presence of long waves, relation (1) assumes the form

$$\begin{aligned}&\sigma_p^0(K, \theta, \alpha, \beta_\uparrow)\\ &= 8K^4|G_p(\theta - \beta_\uparrow)|^2\Xi(\mathbf{k}_B(K, \theta - \beta_\uparrow)),\end{aligned} \tag{4}$$

where $\beta_\uparrow$ is the angle of sea-surface slope produced by the long waves in the direction of incidence of radio waves.

Let the sizes of a radar spot on the sea surface be substantially greater than the wavelengths of long waves. Then, the effect of long waves on the magnitude of a backscattered signal can be taken into account by averaging (4) over the entire range of the related sea-surface slopes $\beta_\uparrow$. The averaging should be made with the weight that determines the probability of occurrence for different values of the angle $\beta_\uparrow$. In this case,

$$\begin{aligned}\sigma_P^L &= \int\sigma_P^0(\theta - \beta_\uparrow)P(\beta_\uparrow)d\beta\\ &= \int 8K^4|G_p(\theta - \beta_\uparrow)|^2\Xi(\mathbf{k}_B(K, \theta - \beta_\uparrow))P(\beta_\uparrow)d\beta,\end{aligned} \tag{5}$$

where $P(\beta_\uparrow)$ is the probability density of slopes in the direction of radio-wave incidence.

In order to implement the averaging procedure in (5), it is necessary to transform the spectrum of the sea surface height Ξ by representing it as an explicit function of the angle of incidence. For this purpose, we switch from the wave-vector spectrum Ξ to the spectrum of wave numbers and directions $\chi(k, \alpha)$:

$$\Xi(k_x, k_y)\frac{\partial(k_x, k_y)}{\partial(k, \alpha)} = \chi(k, \alpha), \tag{6}$$

where the Jacobian $\frac{\partial(k_x, k_y)}{\partial(k, \alpha)} = k$. Further, we represent the spectrum $\chi(k, \alpha)$ in the form

$$\chi(k, \alpha) = S(k)\Theta(k, \alpha), \tag{7}$$

where $S(k)$ is the one-dimensional wave-number spectrum and $\Theta(k, \alpha)$ is the function of the angular distribution of wave energy, which satisfies the normalization condition $\int_{-\pi}^{\pi}\Theta(k, \alpha)d\alpha = 1$.

Let us change the variables in the spectrum $S(k)$:

$$S(k)\frac{dk}{d\theta} = \tilde{S}(K2\sin\theta), \tag{8}$$

where $\frac{dk}{d\theta} = K2\cos\theta$. Finally, we obtain the following expression for σ_B^0:

$$\sigma_B^0 = 2K^2|G_p(\theta)|^2\frac{\tilde{S}(K2\sin\theta)}{\sin\theta\cos\theta}\Theta(k_B, \alpha_B). \tag{9}$$

Because the explicit dependence of σ_B^0 on the angle of incidence is found, it is possible to estimate the corrections that are due to long waves. In calculations of the corrections, surface waves with wavelengths greater than 10 cm will be considered long compared to the Bragg components.

At frequencies higher than the frequencies of dominant waves, the spectra of sea-surface slopes vary only slightly with the frequency. Therefore, the narrowing of the wavelength range of waves that form sea-surface slopes leads to a decrease in the rms slope. The physical mechanisms responsible for the deviation of the higher statistical moments of slopes from their values, which correspond to a Gaussian distribution, also change. Specifically, in our case the effect of capillary ripples that are generated on the crests of gravity waves, which leads to an increase in the asymmetry of the slope distribution, is excluded.

Statistical moments of the slopes that are produced by surface waves in the wavelength range with the lower bound corresponding to a spatial scale of 10 cm have not been estimated previously. Therefore, we start our analysis by determining the statistical

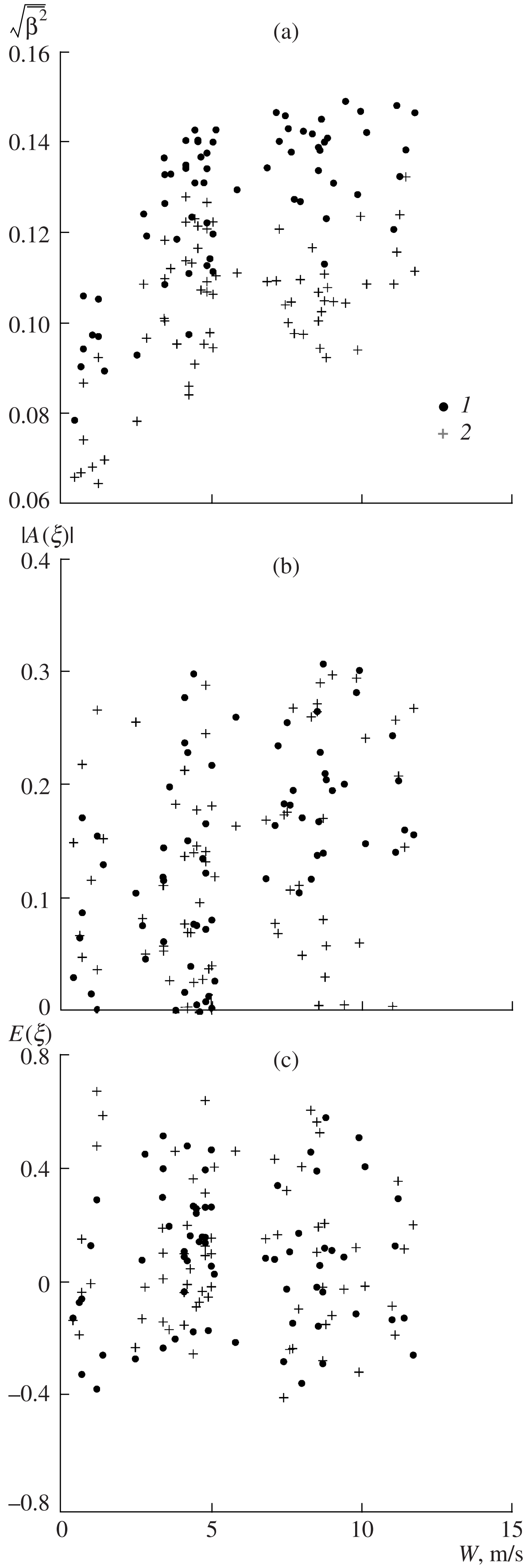

Fig. 1. Statistical characteristics of sea-surface slopes in the (*1*) up/downwind and (*2*) crosswind (with respect to the wind velocity) directions: (a) rms slope $\sqrt{\overline{\beta^2}}$; (b) skewness modulus $|A(\xi)|$, and (c) peakedness $E(\xi)$.

moments of sea-surface slopes formed by the waves of the indicated range.

STATISTICAL CHARACTERISTICS OF SEA-SURFACE SLOPES

For further analysis, we will use the data of in situ measurements of sea-surface slopes on the oceanographic platform of the Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine. This platform is mounted in the Black Sea near the South Coast of the Crimea. The sea depth where the platform is located is 30 m, which corresponds to the deep-water condition for the Black Sea; i.e., the wave-field distortions that are due to the bottom can be disregarded.

Sea-surface slopes were measured with a two-dimensional slopemeter. The measurements were taken with a time step of 0.02 s. Operation of the instrument is based on measuring the angles of deflection of a laser beam during its passage through a rough water–air interface from under the water. The recorded angle of laser-beam deflection from the vertical is determined by a local sea-surface slope at the point (on an area of about 2 mm^2) where this surface is intersected by the beam. The instruments and conditions of measurements are described in [15, 16].

The initial records of sea-surface slopes, which were obtained with a laser slopemeter, contain information about sea-surface slopes in the frequency range to 25 Hz. In order to eliminate the effect of high-frequency components, the initial records of slopes were filtered. The cutoff frequency of the filter was taken equal to 4 Hz. Waves below this frequency are gravity waves, which satisfy the dispersion relation

$$(2\pi f)^2 = gk, \tag{10}$$

where f is the frequency and g is the acceleration of gravity. According to Eq. (10), the wavelength equal to 10 cm corresponds to the frequency of 4 Hz.

The slope records were presented in a Cartesian coordinate system with one of its axes oriented in the wind direction [17].

The sea surface height will be denoted as ζ. The variables $d\zeta/dx = \xi_u$ and $d\zeta/dy = \xi_c$ in the Cartesian coordinate system are considered the up/downwind and cross-wind components of slopes, i.e., the slopes along and across to the wind direction. The statistical moments of the slopes in the up/downwind (ξ_u) and cross-wind (ξ_c) directions are shown in Fig. 1.

Changes in the wavelengths of the Bragg components of surface waves due to a change in the local incidence angle

Local incidence angle	$\frac{\lambda_B\left(\theta \pm n\sqrt{\overline{\beta_u^2}}\right)}{\lambda_B(\theta)}$, $n = 1, 2, 3$			
	$\theta = 35°$		$\theta = 45°$	
$\theta \pm \sqrt{\overline{\beta_u^2}}$	0.85	1.2	0.89	1.2
$\theta \pm 2\sqrt{\overline{\beta_u^2}}$	0.75	1.6	0.82	1.4
$\theta \pm 3\sqrt{\overline{\beta_u^2}}$	0.69	2.5	0.77	1.8

Figure 1 presents estimates for the skewness and peakedness of the distributions of sea-surface slopes produced by waves with wavelengths of 10 cm or longer. These estimates point to the quasi-Gaussian characters of these distributions. It is seen that, on average, the skewness of the distribution of the up/downwind component of slopes increases with the wind velocity. The average skewness for the crosswind component of slopes is close to zero; however, in individual situations, significant deviations from zero are observed. The asymmetry of the distribution of the crosswind component of slopes may be due to the surface current being directed at an angle to the wind velocity vector, as well as to variations in the wind direction, because the rearrangement times of the components of a wave field with different wavelengths differ from one another.

QUANTITATIVE ESTIMATIONS OF A VARIATION IN THE WAVELENGTH OF THE BRAGG COMPONENT

The aforementioned data on sea-surface slopes make it possible to estimate the limits of variations in the wavelength of the Bragg component as a result of variations caused in a local angle of incidence by long waves. Calculations were performed for two angles of incidence of 35° and 45°. If variations in a local angle of incidence are taken into account, the wavelengths of the radio (Λ) and surface (λ_B) waves are related by

$$\lambda_B = \frac{\Lambda}{2\sin(\theta - \beta_\uparrow)}, \tag{11}$$

where $\beta_\uparrow$ is the angle of the sea-surface slope in the radio-sounding direction.

The rms angle of long-wave slopes in the up/downwind direction for the series of slopes under study is $\sqrt{\overline{\beta_u^2}} = 7.3°$. The results of calculating variations in the wavelength of the Bragg components caused by variations in a local angle of incidence during sounding along the wind direction are presented in the table.

The angular distribution of wave energy is anisotropic in the wavelength range of interest. The variance of sea-surface slopes oriented along the wind direction is greater than that for the crosswind direction. Therefore, the effect of long waves on the character of Bragg scattering during sounding in the crosswind (with respect to the wind velocity) direction is smaller than that for the up/downwind direction. The rms angle of slopes in the crosswind direction is $\sqrt{\overline{\beta_c^2}} = 5.9°$. The variation in a local angle of incidence at $\theta = 35°$ leads to relative variations in the wavelength of the Bragg component $\frac{\lambda_B\left(\theta \pm 3\sqrt{\overline{\beta_c^2}}\right)}{\lambda_B(\theta)}$ of 0.72 and 1.9.

EFFECT OF LONG WAVES ON BRAGG SCATTERING (GAUSSIAN DISTRIBUTION)

In order to calculate the backscattering cross section, it is necessary to specify the spectrum of the sea surface height $S(k)$. In the range of wave numbers greater than the wave number of dominant waves, this spectrum is described by the approximation $S(k) \sim k^{-n}$. Parameter n depends on the range of wave numbers. The boundary that separates gravity and gravity–capillary waves is a spatial scale of 7 cm [18]. In the short-wave range, which corresponds to the gravity–capillary range, $n = 3$ can be used [19].

The relations obtained in [20] for the geometric coefficient $|G_p(\theta)|^2$ will be used in calculations. The function $|G_p(\theta)|^2$ may be written as

$$|G_v|^2 = \frac{\cos^4\theta(1+\sin^2\theta)^2}{(\cos\theta + 0.111)^4}, \tag{12}$$

$$|G_h|^2 = \frac{\cos^4\theta}{(0.111\cos\theta + 1)^4}. \tag{13}$$

for the vertical (index v) and the horizontal (index h) polarization, respectively.

The distribution of sea-surface slopes is close to a Gaussian distribution. First, we will analyze the effect of long waves on the backscattering cross section under the assumption that sea-surface slopes obey a Gaussian distribution. Next, we will assess the effects

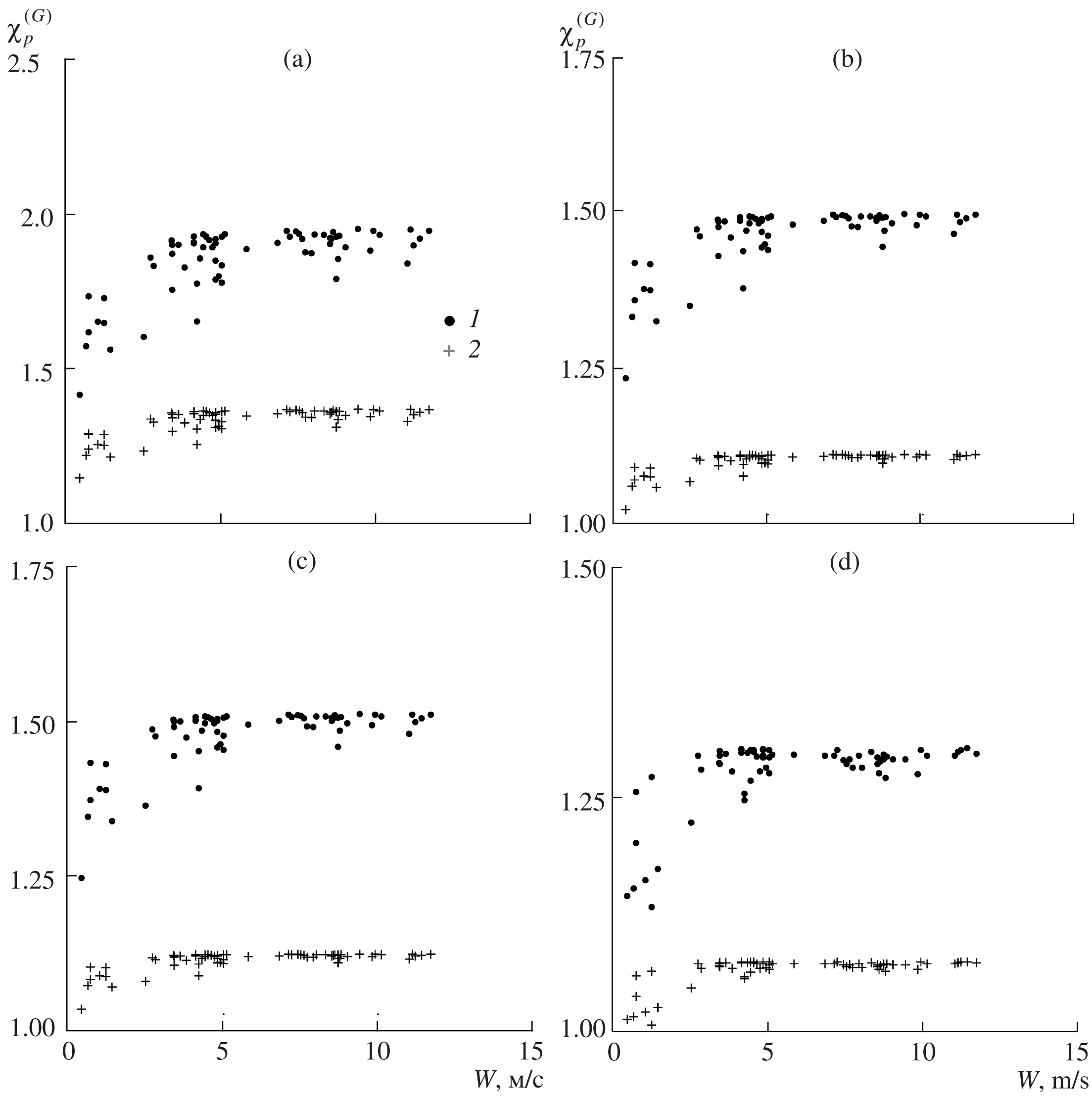

Fig. 2. Dependence of the parameter $\chi_p^{(G)}$ on the wind velocity W for (*1*) the horizontal and (*2*) the vertical polarization: sounding in the (a, c) up/downwind and (b, d) crosswind directions at (a, b) $\theta = 35°$ and (c, d) $\theta = 45°$. The calculation was performed for normal long-wave slopes.

that are due to deviations of the third and fourth statistical moments from their values corresponding to the Gaussian distribution.

Since averaging in expression (5) is performed over the angles of sea-surface slopes, it is necessary to switch from the probability density of the slopes $\tilde{P}(\xi)$ to the probability density of the angles of slopes $P(\beta)$. The slopes ξ and the angles of slopes β are related by $\xi = \tan\beta$. In an analysis of electromagnetic scattering from the sea surface, it is usually assumed that its slopes are small and numerically equal to their angles. This assumption introduces an additional error in calculations of the scattered field.

The procedure of switching from the probability density of slopes $\tilde{P}(\xi)$ to the probability density of the angles of slopes $P(\beta)$ is described by the expression

$$P(\beta) = \frac{d\xi}{d\beta}\tilde{P}(\tan\beta). \qquad (14)$$

For the criterion that determines the effect of long waves on Bragg scattering, we will use the parameter

$$\chi_p(\theta) = \frac{\int \sigma_p^0(\theta - \beta_\uparrow)P(\beta_\uparrow)d\beta_\uparrow}{\sigma_p^0(\theta)}. \qquad (15)$$

The results of estimating the parameter $\chi_p^{(G)}$ for different wind velocities are given in Fig. 2. The upper

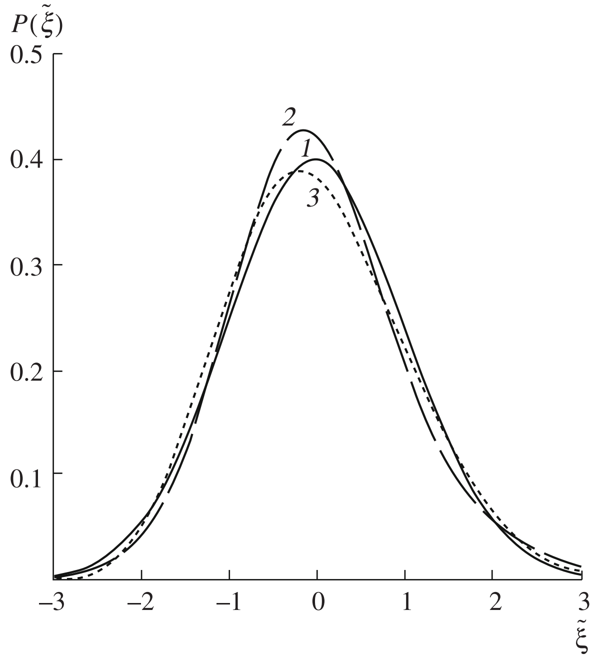

Fig. 3. Models for the probability density: (*1*) a Gaussian distribution and (*2*, *3*) two distributions constructed from a Gram–Charlier series with $A = 0.3$, $E = 0.5$ and $A = 0.3$, $E = -0.3$, respectively.

index G implies that calculations were performed for a Gaussian distribution of sea-surface slopes.

Variations in local sea-surface slopes caused by long waves lead to an increase in the backscattering cross section. This increase occurs for sounding at both horizontal and vertical polarization. This effect manifests itself to a greater extent for radars operating at the horizontal polarization. The degree of influence of long waves on the backscattering cross section also depends the angle of incidence of radio waves θ defined with respect to the plane surface. As the angle θ increases, the influence of long waves reduces.

EFFECTS CAUSED BY A QUASI-GAUSSIAN DISTRIBUTION OF SEA-SURFACE SLOPES

Experimental studies have shown that the distributions of sea-surface slopes are not Gaussian in the strict sense [15, 21]. Departures from a Gaussian distribution are due to a number of factors. The main factor is the interactions of waves with different scales [22, 23].

Approximations constructed on the basis of a Gram–Charlier series are used to model probability densities for quasi-Gaussian distributions [24]. The coefficients of a Gram–Charlier series are calculated from empirical estimations of the statistical moments of slopes. Since statistical moments through the fourth order are usually determined in experiments, only the first five terms of the Gram–Charlier series are taken into account in modeling. With the use of the normalization $\tilde{\xi} = \xi/\sqrt{\overline{\xi^2}}$, the approximation of the probability density of slopes may be written as

$$P_s(\tilde{\xi}) = \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\tilde{\xi}^2}{2}\right) \times\left(1 + \frac{A(\tilde{\xi})}{6}H_3(\tilde{\xi}) + \frac{E(\tilde{\xi})}{24}H_4(\tilde{\xi})\right). \tag{16}$$

The peakedness values for the components of sea-surface slopes produced by waves longer than 10 cm mostly vary from –0.3 to 5. Figure 3 shows the functions $P_s(\tilde{\xi})$ constructed for the above peakedness values and for a skewness of 0.3.

Variations in the skewness and peakedness of slopes lead to variations in the parameter $\chi_p^{(K)}$. Here, the upper index Q indicates that calculations by formula (15) are carried out for a quasi-Gaussian distribution. The dependence of $\chi_p^{(K)}$ on skewness variations is not unique; it depends on whether sounding is performed along the wind or in the opposite direction. An increase in the skewness of the distribution of slopes leads to an increase in $\chi_p^{(K)}$ in the first case and to a decrease in $\chi^{(Q)}$ in the second case.

In order to assess the extent to which the nonlinearity of long surface waves, which is responsible for the departure of the distribution of sea-surface slopes from a Gaussian distribution, affects the backscattering cross section, we will consider the parameter

$$\varepsilon_p = \chi_p^{(K)}/\chi_p^{(G)}. \tag{17}$$

The dependence of the parameter ε_p on the skewness of the distribution of slopes is shown in Fig. 4. Negative skewness values correspond to sounding in the wind direction. Calculations were performed for the sounding angle $\theta = 35°$ and for $\sqrt{\overline{\beta_{\uparrow}^2}} = 7.3°$. The backscattering cross section in the radio sounding of the sea surface at different forms of polarization is affected to a variable extent by the skewness of the distribution of slopes. Its effect turns out to be stronger if the polarization is horizontal. The value of the parameter ε_p is only slightly affected by variations in the peakedness of the distribution of slopes within the limits of an experimental spread of their individual values.

Studies of sea-surface slopes point to strong variations in their statistical moments [16, 21]. The statistical moments are weakly correlated with one another. Therefore, it is useful to analyze how the values of the parameter ε_p vary in individual situations. Its values estimated for different wind velocities are presented

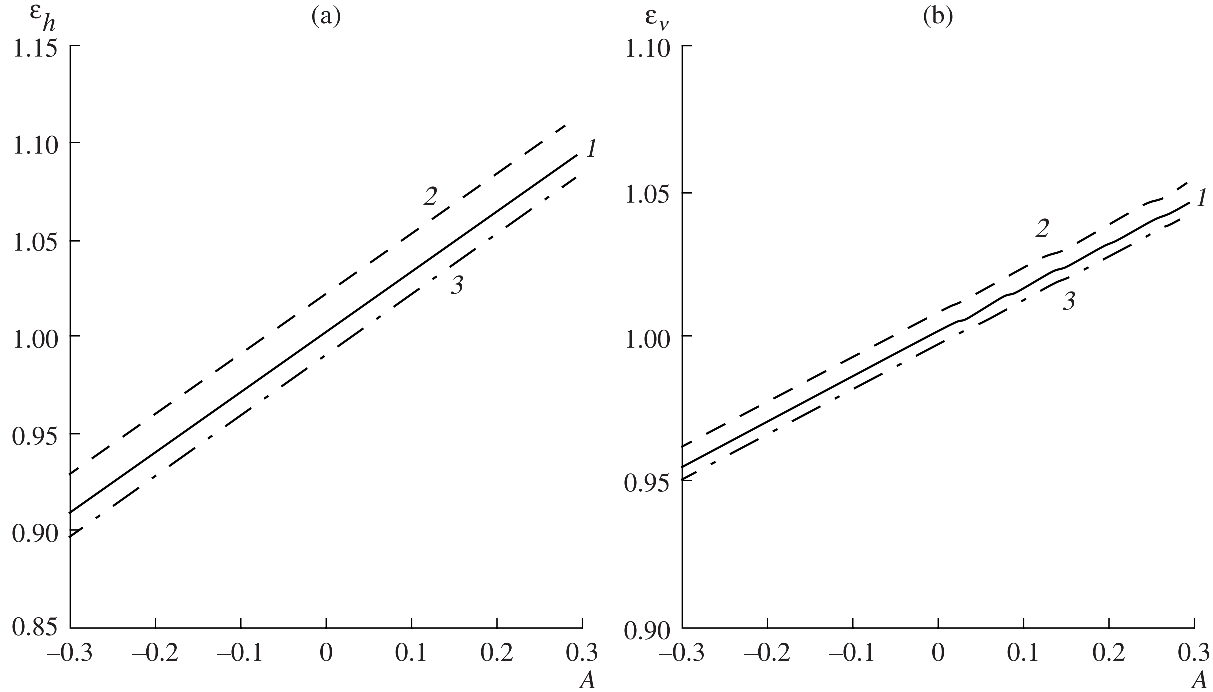

Fig. 4. Dependence of the parameter ε_p on the skewness A and peakedness E of the distribution of sea-surface slopes: (*1*) $E = 0$, (*2*) $E = 0.5$, and (*3*) $E = -0.3$.

in Fig. 5. The calculations were carried out in two variants which corresponded to radio sounding along the wind and in the opposite direction. For the horizontal polarization, the skewness of the distribution of slopes may cause the backscattering cross section to deviate from the model estimate obtained for a Gaussian distribution by 15% (at $\theta = 35°$). For vertical polarization, deviations from the estimates obtained for the backscattering cross section from a Gaussian distribution are about two times smaller.

INFLUENCE OF LONG-WAVE SLOPES ON ESTIMATES FOR NEAR-WATER WIND VELOCITY

Wind-measuring instruments mounted on space vehicles are calibrated against data obtained from meteorological buoys. The present-day accuracy of measuring the near-water wind velocity from space vehicles is about 1.7 m/s [25]. This accuracy was achieved even in the first algorithms, where the backscattering cross section was used as the only predictor, and has not been improved for one-parameter models up to now.

The accuracy of measuring the near-water wind is determined by engineering and physical factors. An engineering factor involves a misalignment of the buoy's location and the satellite's path, the absence of synchronism in measurements, and instrumental errors. A physical factor lies in the validity of the algorithm used to calculate the wind velocity from the backscattering cross section, i.e., to what extent the parameters of the scattering model are related to the wind speed under real conditions. These factors are to be assessed to choose a way to improve the accuracy of measuring the near-water wind.

The right-hand side of (5) contains two characteristics of the sea surface which are statistically related to the wind velocity W, and this relation controls the accuracy of its determination. These characteristics are the spectrum of surface waves $\Xi(\mathbf{k}_B)$ and the probability density of sea-surface slopes $P(\beta_\uparrow)$. The error due to a stochastic relationship between $\Xi(\mathbf{k}_B)$ and W was analyzed in [26], where it was noted that this relationship represents a fundamental limitation on the possible accuracy of determining W. Here, we will analyze how the ambiguity of the dependence of statistical characteristics of long waves on the wind velocity affects the accuracy of its scatterometric determination.

From the results of an analysis of the Black Sea radar images obtained by the Sich-1 satellite during sounding at a wavelength of 3.2 cm and at the vertical polarization, the recorded backscattering cross section may be written as [27]

$$\sigma \sim W^{4.98 - 0.62\ln(W)}. \tag{18}$$

The ambiguity of the wind-velocity dependence of the angles β causes the relation $\sigma = \sigma(W)$ (which forms the

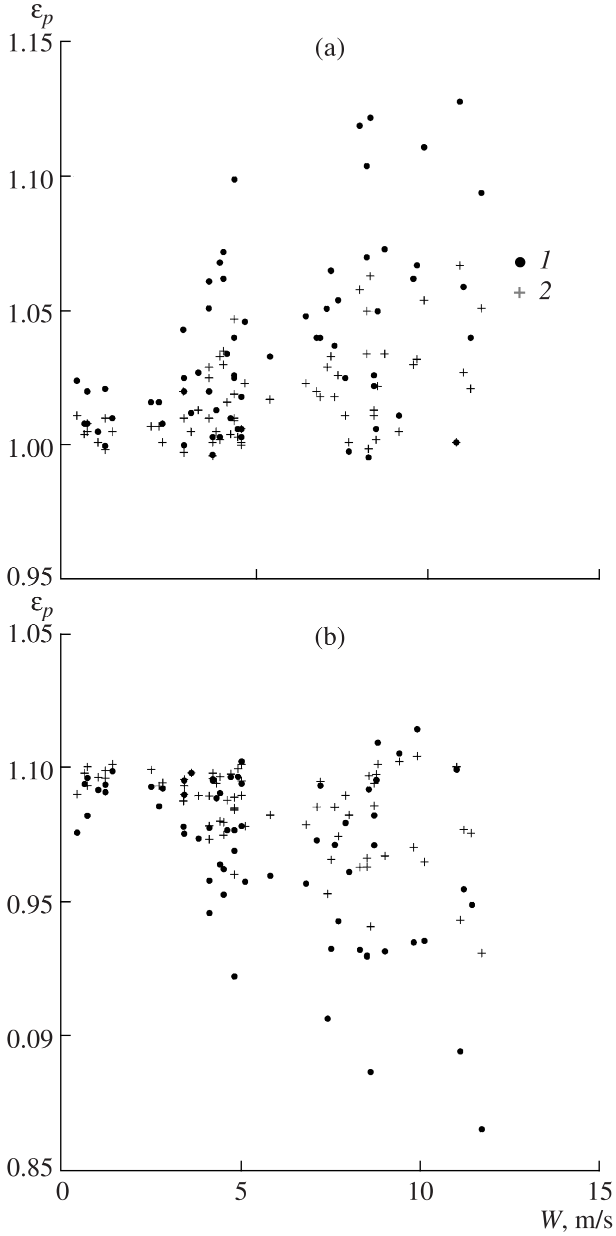

Fig. 5. Dependence of the parameter ε_p on the wind velocity W as inferred from empirical estimates for the skewness and peakedness of the distribution of the up/downwind-slope component: (a) sounding in the direction opposite to the wind and (b) sounding along the wind. (*1*) and (*2*) correspond to the horizontal and the vertical polarization, respectively.

basis for the radar determination of the near-water wind velocity) to assume the form $\sigma = \sigma(W) + F$, where F is a stochastic function. The values of function F are controlled by a wide number of physical factors, including the stage of wave development, the fetch length and surface flow.

The spread of rms slopes about their mean is 0.09 for the velocity range $4.5 < W < 5.5$ m/s and 0.06 for the velocity range $9.5 < W < 10.5$ m/s. For this spread, the error caused in the scatterometric determination of the wind velocity by long waves is 15 cm/s if $W \approx$ 5 m/s and 50 cm/s if $W \approx 10$ m/s. These estimates are obtained for sounding at the vertical polarization along the wind direction at the incidence angle $\theta = 40°$.

CONCLUSIONS

The effect of sea wind waves that are longer than the Bragg components on radio-wave backscattering was analyzed for centimeter waves. A situation was studied in which waves with wavelengths greater than 10 cm are longer than the Bragg components.

It should be noted that one fundamental difference in the results of this study from those of recently published works on radio-wave scattering from the sea surface [11–13, 28] is the fact that they were obtained from the data of direct field measurements. As a result, it was possible to assess the influence of real departures of the distribution of sea-surface slopes from a Gaussian distribution and, in particular, to show the significance of nonzero skewness values of the distribution of slopes for Bragg scattering.

When sounding is performed along the wind or in the opposite direction, nonzero skewness values of the distribution of slopes may lead to a 15% deviation of the backscattering cross section from its value calculated for a Gaussian surface at $\theta = 35°$. At the same incidence angle and at the vertical polarization, the deviations from the estimates obtained for the backscattering cross section with a Gaussian distribution are about two times smaller. Nonzero values of the peakedness of the distribution of slopes, which are observed in wave experiments, can be neglected in calculations of the backscattering cross section.

The geometric effects that are due to variations in local sea-surface slopes lead to an increase in the backscattering cross section. These effects are more clearly defined when the radar operates at the horizontal polarization. When sounding is performed at the angle $\theta = 35°$, a change in the backscattering cross section during strong winds attains 50% at the horizontal polarization and 35% at the vertical polarization.

We also note that the widely used calculation of scattered fields on the basis of analytic spectral models of the sea surface [2, 29] or models constructed on the basis of laboratory measurements [28] basically does not allow estimating the error due to a stochastic relationship between the characteristics of the sea surface and the wind velocity. Such an analysis is possible only on the basis of the data from measuring the characteristics of the sea surface. At a given wind velocity, the spread of the statistical characteristics of the sea-surface slopes that are produced by surface waves longer than the Bragg components is a factor that limits the possible accuracy of the scatterometric determination of the wind velocity. If sounding is performed along the wind velocity at the vertical polarization at the incidence angle $\theta = 40°$, the error that is due to this factor is 15 cm/s and 50 cm/s at a wind velocity of 10 m/s.

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REFERENCES

1. S. O. Rice, "Reflection of Electromagnetic Waves from Slightly Rough Surfaces," Com. Appl. Math. **4**, 361–378 (1951).
2. V. N. Kudryavtsev, D. Hauser, G. Caudal, and B. Chapron, "A Semiempirical Model of the Normalized Radar Cross-Section of the Sea Surface," J. Geophys. Res. C **108**, FET2 1–24 (2003).
3. V. I. Shrira, S. I. Badulin, and A. G. Voronovich, "Electromagnetic Wave Scattering from the Sea Surface in the Presence of Wind Wave Patterns," Int. J. Remote Sensing **24**, 5075–5093 (2003).
4. R. Mur and A. K. Fen, "Radar Determination of the Parameters of Wind over a Sea," Proc. IEEE **67**, 40–63 (1979).
5. R. K. Moore and W. J. Pierson, "Measuring Sea State and Estimating Surface Winds from a Polar Orbiting Satellite," in *Proceedings of the International Symposium on Electromagnetic Sensing of the Earth from Satellites* (Miami Beach, 1966).
6. A. S. Zapevalov and V. V. Pustovoitenko, "On the Accuracy of Scatterometric Determination of the Near-Water Wind," in *Ecological Safety of Coastal and Shelf Zones and a Complex Use of Shelf Resources* (MGI NANU, Sevastopol, 2004), No. 11, pp. 262–267 [in Russian].
7. W. C. Keller and J. W. Wright, "Microwave Scattering and the Straining of Wind-Generated Waves," Radio Sci., No. 10, 139–147 (1975).
8. K. I. Volyak, "Determination of Waviness Parameters from Radio Images of the Sea," Issled. Zemli Kosmosa, No. 6, 86–94 (1982).
9. V. V. Malinovskii, "Features of Calculating the Geometric Coefficient in a Two-scale Model of the Sea Surface Effective Scattering Cross Section," Issled. Zemli Kosmosa, No. 1, 30–35 (2004).
10. J. C. West, B. S. O' Leary, and J. Klinke, "Numerical Calculation of Electromagnetic Scattering from Measured Wind-Roughened Water Surfaces," Int. J. Remote Sensing **19**, 1377–1393 (1998).
11. G. Berginc, "Small-Slope Approximation Method: a Further Study of Vector Wave Scattering from Two-Dimensional Surfaces and Comparison with Experimental Data," Progr. Electromagn. Res. **37**, 251–287 (2002).
12. Borge J. C. Nieto, G. N. Rodriguez, K. Hessner, and P. I. Gonzalez, "Inversion of Marine Radar Images for Surface Wave Analysis," J. Atmos. Ocean. Technol. **21**, 1291–1300 (2004).
13. E. J. Walsh, M. L. Banner, C. W. Wright, et al., "The Southern Ocean Waves Experiment. Part III: Sea Surface Slope Statistics and Near-Nadir Remote Sensing," J. Phys. Oceanogr. **38**, 670–685 (2008).
14. F. G. Bass and I. M. Fuchs, *Wave Scattering from Statistically Rough Surfaces* (Nauka, Moscow, 1972; Pergamon, Oxford, 1978).
15. G. N. Khristoforov, A. S. Zapevalov, and M. V. Babii, "Statistical Characteristics of Sea-Surface Slopes at Different Wind Speeds," Okeanologiya **32**, 452–459 (1992).
16. A. S. Zapevalov, "Variations in the Characteristics of Local Sea-Surface Slopes," Prikl. Gidromekh. **7(79)**, 17–21 (2005).
17. B. A. Hughes, H. L. Grant, and R. W. A. Chappell, "A Fast Response Surface-Wave Slope Meter and Measured Wind-Wave Components," Deep-Sea Res. **24**, 1211–1223 (1977).
18. J. Lighthill, *Waves in Fluids* (Cambridge Univ. Press, Cambridge, 1978; Mir, Moscow, 1981).
19. A. S. Monin and V. P. Krasitskii, *Phenomena on the Ocean Surface* (Gidrometeoizdat, Leningrad, 1985) [in Russian].
20. W. J. Plant, "A Two-Scale Model of Short Wind Generated Waves and Scatterometry," J. Geophys. Res. C **91**, 10 735–10 749 (1986).
21. C. Cox and W. Munk, "Statistics of the Sea Surface Derived from the Sun Glitter," J. Mar. Res. **13**, 198–227 (1954).
22. M. S. Longuet-Higgins, "On the Skewness of Sea-Surface Slopes," J. Phys. Oceanogr. **12**, 1283–1291 (1982).
23. A. V. Babanin and V. G. Polnikov, "On a Non-Gaussian Property of Wind Waves," Morsk. Gidrofiz. Zh., No. 3, 79–82 (1994).
24. M. G. Kendall and A. Stuart, *The Advanced Theory of Statistics*, 4th ed. (Griffin, London, 1977; Nauka, Moscow, 1966).
25. V. Yu. Karaev, M. B. Kanevskii, G. N. Balandina, and D. Kotton, "Three-Parameter Algorithm for Determining the Surface-Wind Velocity from Radio-Altimetric Measurements," Issled. Zemli Kosmosa, No. 6, 33–41 (1999).
26. G. N. Khristoforov, A. S. Zapevalov, and V. E. Smolov, "On the Limiting Accuracy of Scatterometric Determination of the Wind Velocity over the Ocean from a Satellite," Issled. Zemli Kosmosa, No. 2, 57–65 (1987).
27. V. V. Malinovskii, "Possibility of Mapping the Wind Velocity over the Black Sea from the Data of the Sich-1 Satellite Side-Looking Radar," in *Ecological Safety of Coastal and Shelf Zones and a Complex Use of Shelf Resources* (MGI NANU, Sevastopol, 2004), No. 11, pp. 226–235 [in Russian].
28. W. J. Plant, "A Stochastic, Multiscale Model of Microwave Backscatter from the Ocean," J. Geophys. Res. **107**, doi: 10.1029/2001JC000909, 3120 (2002).
29. T. Elfouhaily, B. Chapron, K. Katsaros, and D. Vandemark, "A Unified Directional Spectrum for Long and Short Wind-Driven Waves," J. Geophys. Res. **102**, 15 781–15 796 (1997).