SPECTRAL CHARACTERISTICS OF A MICROWAVE RADAR SIGNAL BACKSCATTERED BY THE SEA SURFACE AT SMALL INCIDENCE ANGLES

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We present a theoretical analysis of the Doppler-spectrum properties of a microwave radar signal scattered by the sea surface at small incidence angles. The dependences of Doppler-spectrum width and shift on the wind velocity and wave development stage and their azimuthal dependence are analyzed. The case of mixed sea (wind wave plus swell) is also considered. The JONSWAP spectrum model is used to describe sea waves. The study shows that Doppler-spectrum parameters are sensitive to variation of sea-surface state; for example, for the case of developed sea waves, an increase in wind velocity by 1 m/sec leads to increases in the Doppler-spectrum width and shift by 15 Hz and 3 Hz, respectively. It is shown that for the case of a moving radar the Doppler spectrum remains sensitive to variation of sea-surface state with a sufficiently narrow radar directivity pattern. Estimates show that in the case of a single sea-wave system on the surface, using Doppler-spectrum parameters we can, in principle, determine wave type (developing wind wave, developed wind wave, or swell), dominant wavelength, wave propagation direction, and wave height; wind velocity, direction, and acceleration distance can be determined for wind waves.

1. INTRODUCTION

To study hydrophysical processes that occur on the sea surface, and to test and improve the existing models of electromagnetic-wave scattering, the spectral properties of reflected radar signals are used more and more often [1, 2, 3]. Therefore, improvement of the theoretical model of the Doppler spectrum and analysis of its properties compared with experimental results are important.

In this paper we continue the theoretical study [4] of the Doppler spectrum of an a microwave radar signal reflected from the sea surface. This paper deals with the dependence of Doppler-spectrum parameters (width and shift) on the sea-surface state for small incidence angles. This problem has been analyzed in only a few papers [5, 6, 7] and needs further investigation.

Since in the region of small incidence angles the Doppler spectrum of the reflected field depends only on energy-carrying waves, it can be used to find the properties of large-scale waves, which is confirmed by the results given below.

2. WAVE-SPECTRUM MODEL

To describe the energy-carrying waves, we use the known JONSWAP spectrum of surface elevations $\zeta$ supplemented by the angular dependence [8]

$$W(\kappa, \phi) = \frac{\alpha}{2} \kappa^{-3} \exp \left[ -1.25 \left( \frac{\kappa}{\kappa_m} \right)^{-2} + \ln \gamma \cdot \exp \left\{ -\frac{(\sqrt{\kappa/\kappa_m} - 1)^2}{2b^2} \right\} \right] Q(\kappa, \phi),$$

$$Q(\kappa, \phi) = \frac{\Gamma(1 + p/2)}{\pi^{1/2} \Gamma(0, 5 + p/2)} \cdot \cos^{2p}(\phi - \phi_0), \quad |\phi - \phi_0| \leq \pi/2,$$

where \( \kappa_m = \omega_m^2 / g \) is the wave number, which corresponds to the spectral maximum \( \omega_m \) of the JONSWAP frequency spectrum, \( \phi_0 \) is the angle between the general direction of waves and the \( X \) axis, and \( U_{19} \) is the wind velocity at an altitude of 19.5 m. The quantity \( U_{10} \) that occurs everywhere below is the wind velocity at an altitude of 10 m and is related to \( U_{19} \) by the logarithmic wind velocity profile for neutral conditions (see, for example, [9]).

In the case of wind waves, the values of \( \kappa_m \) are found if we use the empirical relations [10, 11] /
\[
\begin{align*}
\omega_m &= \frac{2 \bar{\omega} - 0.33}{\bar{\omega}} \quad \text{for developing waves}, \\
\omega_m &= 0.83 \quad \text{for developed waves},
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where \( \omega_m = \omega_m U_{10} / g \), \( \bar{\omega} = \bar{\omega} / U_{10} \), \( U_{10} \) is the wind velocity at an altitude of 10 m and is related to \( U_{19} \) by the logarithmic wind velocity profile for neutral conditions (see, for example, [9]).

For the surface-elevation dispersion \( \sigma_z^2 \) we know from the experiment [10] that
\[
\sigma_z^2 = 1.6 \cdot 10^7 \bar{\omega} U_{10}^4 / g^2.
\]

Equating Eq. (3) and spectrum integral (1), we find the coefficient \( \alpha \), which has not yet been determined. It is noteworthy that acceleration value \( \bar{\omega} \approx 2 \cdot 10^4 \), for which developing waves enter the regime of entirely developed waves, is estimated from the relation \( 22\bar{\omega} - 0.33 = 0.83 \) (see Eq (2)) and gives the known quantity \( \alpha = 0.0081 \), which is normally used for developed wind waves.

Let us assume the following swell-spectrum model. Let us assume that \( \gamma = 10 \) [8] and choose specific values for the dominant wavelength \( \Lambda_m = 2\pi / \kappa_m \): 100 m, 150 m, 200 m, and 250 m. Assuming that swell height \( H = 4\sigma_z \), we obtain the corresponding values of \( \alpha \); in this case we should bear in mind that \( H \) has restrictions from above. We assume that the swell-spectrum maximum cannot exceed the corresponding value for developed waves for similar \( \Lambda_m \), from which it follows that \( \alpha < 0.0081 / \gamma = 0.00081 \).

For the mixed-sea spectrum (for example, wind waves plus swell) different approximations exist. However, if the spectrum maxima of different wave systems are sufficiently separated, the mixed-sea spectrum is simply found from the sum [12]
\[
W_\zeta(\kappa, \phi) = W_w(\kappa, \phi) + W_s(\kappa, \phi),
\]
where \( W_w(\kappa, \phi) \) and \( W_s(\kappa, \phi) \) are the spectra of wind waves and swell, respectively.

3. DOPPLER-SPECTRUM PARAMETERS. CALCULATION FORMULAS AND RESULTS

The sounding pattern for the sea surface is given in Fig. 1. A coherent radar is located on a carrier that travels with velocity \( V \) in parallel to the \( Y \) axis. Observation is performed laterally for the incidence angle \( \theta_0 \), which is assumed to be sufficiently small such that the backscattering mechanism of a microwave radar signal (incident wavelength \( \lambda \)) is quasispecular rather than Bragg's. The antenna directivity pattern, which is assumed to be Gaussian, has its half-width \( \delta_x \) in the vertical plane and \( \delta_y \) in the azimuthal plane for power level 0.5.