Statistical properties of SHF radar sea return: fine structure of temporal and spatial spectra

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Radar sensing of the ocean surface can yield information about sea state and wind speed and direction. Radar backscattering is dominated by the Bragg scattering mechanism (Barric, 1972). At microwave frequencies (SHF), backscattering is from capillary waves riding on top of large-scale wind waves and swell, which modulate the radar return (Bass and Fuks, 1979).Amplitude and phase of modulation depend on wave slope and orbital velocity. Experimental investigations of the modulation effect of the scattering signal by large-scale waves were presented in many papers (e.g. Kalmykov and Pustovoytenko, 1976; Wright et al., 1980). The most of authors studied a integrated temporal characteristics of the received signal, for example, modulation transfer function (Wright et al,1980).In present work we made the attempt to study fine structure of radar signals by digital processing. For experimental investigation of spatial and temporal structure of radar sea return two different methods were used, but in both cases we applied similar digital methods,particularly, spectrum average at moving interval. Influence of the large-scale surface waves on the structure of radar sea echo was analyzed by spatial measurements on "frozen" surface (Volkov et al,1991). Fine variations of Doppler spectrum gives us the possibility to obtain some information about capillary- gravitational waves which are modulated by large-scale waves. We investigated a deviation of radar signal statistical distribution from the Raleigh one and deviation of results obtained from "two scale" model.

Experimental arrangement and instrumentation:

As a location system we had a ship-board incoherent search radar. The radar used two transmitting/receiving antennas, operating at 3 and 10 cm wavelengths (horizontal polarization), that scanned 360° of azimuth in 3.45 s and which were located at height H =25 m above mean sea level. The antennas had azimuthal beamwidth g =0.75° and g =2.5 °at 3 dB level for 3 and 10 cm, respectively. The vertical beamwidths were 20° for both wavelengths. The radar pulse duration t was 0.4 μs, giving a range resolution 60 m. Sampling rate of the signal envelope was 20 MHz on interval 0<t<50 μs,which corresponds to location range 0 -7.5 km. This time interval is sufficiently short compared with all ocean periods so that the sea surface could be treated as if it was "frozen". Thus, described technique permits you to study spatial (rather than temporal) characteristics of the waved sea surface in certain direction.

For phase measurements we used special Doppler radar with continuous radiation 20 GHz. Radar specificity - obtaining of Doppler shift without intermediate frequency, by direct mixing of radiat ion with receiving signal(similar to Abou-Taleb et al,1986). We carried out measurements from moving ship . Diameter of illuminat ed area was 1.5 - 2 m. Frequency shift changed in limits 100-500 Hz.Sampling rate 1 - 2 kHz during 10 - 20 s. It gives us the poss ibility to obtain enough resolution for fine structure analyzing, on the other hand, - to estimate influence of large-scale waves with period about few seconds.

Results and conclusions:

Spectrum averaging at moving interval gives us the possibility to obtain statistical stability of spectra during short time interval which corresponds to different distance(or incidence angle) for spatial observations. For phase observations such interval corresponds to diameter of illuminated area.

When analyzing radar signal reflected from the surface and modulated by large waves, one must keep in mind that signals spectrum is due to non-linear relation between the reflected signal intensity and the local depression angle. For horizontal polarization of the transmitted and received radiation the sea spikes echoes certainly become important and can give contribution to generating non-linear harmonics into fluctuation spectra (Kalmykov and Pustovoytenko, 1976). Nevertheless, when surface contains only smooth roughness, connection between the backscatter cross section σ and local grazing angle q in frames of two-scale surface model is also non-linear and can be expressed by the formula (Valenzuela, 1978)

$$\sigma = 16\pi k_0 \sin^4(q)\ a(q)\ W(k_2)$$

where k_0 is the wave number of radiation, $W(k_2)$ is spectral density of surface waves near k_2, k_2 - wave number of the ripple wave on which the Bragg scattering is formed and a(q) is a factor depending on the radiation polarization and water permittivity.

Fig.1 shows a typical average spatial spectrum of the echo signal from chosen direction (curve 1) and modeling one (curve 2) [Dolin,Rodin,1980]. Section I corresponds to surface wave spectrum, and section II is the spectrum "doubling" due to non-linear effect of "detection". When the grazing angle f decreases, i.e. with increasing of distance r, the non-linearity must be displayed more distinctly. It is explained by the fact that with decreasing of the angle f the linear with respect to α (surface slope) term in the expansion over $q=f-\alpha$ decreases while the square-low one remains constant (see Dolin and Rodin, 1980). This fact is illustrated in the Fig.2 which shows average energy spectra of received signal realizations in dependence on the range r. To obtain these plots we performed the Fourier transform using intervals of realizations with duration Δt=12.8 μs beginning with certain t_0 connected with various grazing angles f (see Fig.2). It can be seen from the Figure that when angle f decreases the height of the the second section in the spectrum increases with respect to the first one.

Fig.3 shows a typical average Doppler spectrum. Spectrum contain coupled peaks, which correspond to Bragg scattering from gravitational-capillary waves moving in opposite directions. Amplitude and frequency shift of peaks give some information about inhomogeneity of the ripple. Fig.4 shows a typical average spectrum in frequency interval near Bragg peaks. It was founded, that peaks frequency position is deviated from main spectrum shift. This fact may be explained by influence of intermediate range of wavelengths and by deviation from "two-scale" model. Farther we studied fine structure of signals near anomalous spikes which result in statistical distribution. Statistical properties of signals from spatial and temporal observations were compared.

Thus, we could obtain some information about all wavelengths of surface waves - from hundred meters to centimeters.

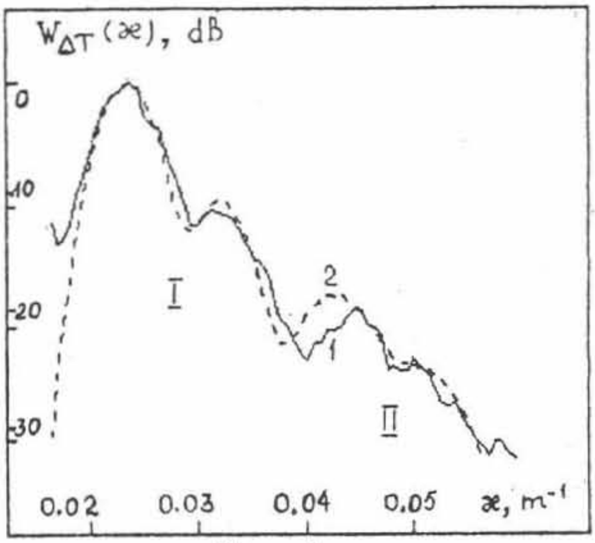


Fig. 1

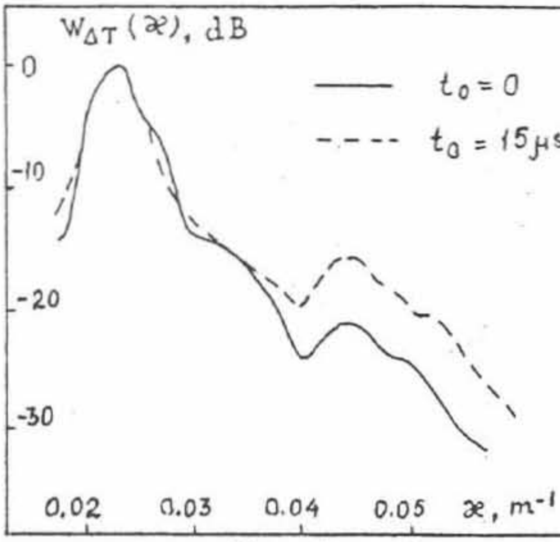
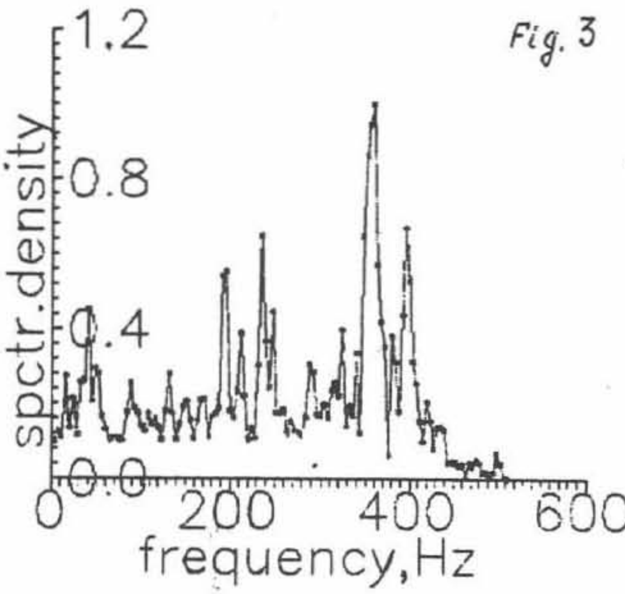
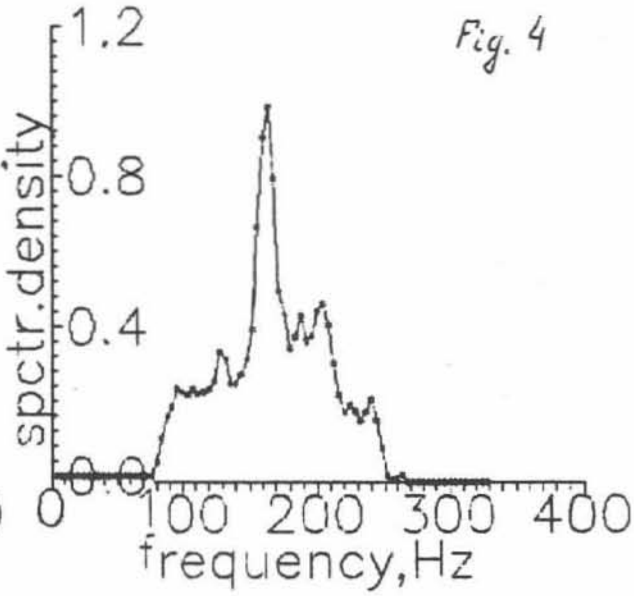


Fig. 2





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