CROSS-POLARIZATION GEOPHYSICAL MODEL FUNCTION FOR MARINE WIND SPEED RETRIEVAL: LABORATORY MODELING AND EXAMPLES OF HURRICANE WIND SPEED RETRIEVAL FROM SATELLITE IMAGERY

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ABSTRACT

Laboratory experiments directed to investigation of dependencies of the X-band normalized co-polarized and de-polarized radar cross-section on wind speed (U_{10}) and incident angle (θ) are presented. Parameters of air-flow velocity and surface wind waves were measured simultaneously. It was shown that both co-polarized and depolarized radar return depend on incidence angle; the depolarized return is less sensitive. Analysis of the Doppler spectra of the radar backscatter enabled us to conclude that the radar return is formed by resonant scatters moving with the velocity exceeding in 20% the phase velocity of the energy containing surface waves. Basing on the measurements the X-band and C-band geophysical model functions (GMF) were derived for U_{10} =10 - 40 m/s and θ=30° – 60°. Examples of hurricane wind speed retrieval with the use of the new GMF are discussed.

Index Terms— co-polarized and depolarized radar return; hurricane wind speed

1. INTRODUCTION

Extreme storms and hurricanes represent a major challenge society worldwide. Among them tropical cyclones seem to be the most hazardous marine weather phenomena, which develop mainly in the tropical area, but can impact on weather in middle latitudes due to extratropical transition. Intense, quickly developing atmospheric vortexes which have mechanisms of generation and some morphological features similar to tropical cyclones (polar hurricanes) re observed at high latitudes. Intense deep cyclones often formed in the north-eastern Atlantic are characterized by conditions of storm and hurricane winds. High values of the wind velocity and the wind loads related to them represent the major factor of the most destructive natural phenomena. This leads to increased requirements for the accuracy of modeling and operational forecasting storm events, which heavily depends on quality of data.

The prevailing methods of monitoring wind speeds and directions over sea surface with high spatial and temporal resolution, which is vital for storm forecasting, employ satellite based scatterometers and Synthetic Aperture Radars (SAR). The key outstanding difficulty is that the existing algorithms of retrieving wind cease to be effective for very strong winds, as the dependence of Normalized Radar Cross Section (NRCS) on wind or Geophysical Model Function (GMF), which underpins all existing algorithms, saturates at winds exceeding 20-25 m/s (see e.g.[1]). Recently analysis of dual- and quad-polarization observations by satellite Radarsat-2 carried out with co-located concomitant direct measurements of wind from oceanographic buoys [2-5], airborne wind measurements by Stepped-Frequency Microwave Radiometer (SFMR) [6,7] and H*Wind data [7] suggested that the cross-polarization GMF keep higher sensitivity to wind speed at stormy and hurricane winds. However it is not straightforward to build a new wind retrieving algorithm upon these very promising observation. Co-located simultaneous observations from satellites and buoys are very rare, and at present there are no reported observations for wind speeds exceeding 26 m/s [7]. Complete collocation of SFMR data with SAR acquisitions is problematic and these two sets of data are compared only statistically. Physical background for these statistical dependencies can be obtained in controlled laboratory conditions, because the depolarized radar return is mostly formed due to backscattering at small-scale features of the sea surface like short-crested waves, sea spray, foam etc, which can be reproduced in laboratory tanks. This paper presents preliminary data of laboratory experiments on a high-speed wind-wave flume of Institute of Applied Physics, which are devoted to the investigation of the X-band co-polarized and depolarized radar return in a wide range of high speeds (from 8 to 40 m/s). In particular the laboratory modeling enabled us to study an open question of dependence of cross-polarized NRSC on the incidence angle, which is difficult for field measurements.

2. EXPERIMENTAL FACILITY

The experiments were performed in the Wind-wave flume of the Institute of Applied Physics [8] with the straight working part of 10 m and operating cross section 0.40×0.40 m^2, the axis velocity can be varied from 5 to 25 m s^{-1} (corresponds to U_{10} from 7 m s^{-1} to 40 m s^{-1}). Parameters of the air flow in the turbulent boundary layer (friction velocity u_* and roughness height z_0) were retrieved by velocity profiling and subsequent data processing based on self-similarity of the turbulent boundary layer in the flume described in [8]. Then the equivalent 10-m wind speed was calculated by definition: $U_{10}=2.5u_*\ln(10m/z_0)$. Three dimensional frequency-wave-number spectra of surface $S(\omega,k,\theta)$ waves and 2-dimensional probability density function (PDF) of "long waves" were retrieved from measurements of the water elevation by three-channel wire gauges by the Fourier directional method (FDM) [8]. The high frequency part of the saturation wave-number spectrum at 1 cm^{-1}<k<4 cm^{-1} can be approximated by a power function with the parameters depending on U_{10} [9] as follows:

$$B(k,\theta)=2/\pi\alpha k^{\beta}\cos^2(\theta), \quad (1)$$

The dependence of α and β on U_{10} are collected in Table 1.

Table 1. Parameters of the saturation wave-number spectrum

U_{10}, m/c	12.4	13.7	15.4	16.9	19.7	21.0
α	0.014	0.013	0.013	0.014	0.016	0.017
β	-1.05	-0.856	-0.589	-0.241	-0.062	-0.141
U_{10}, m/c	24.58	26.2	28.7	30.2	33.3	35.4
α	0.021	0.023	0.027	0.030	0.032	0.034
β	-0.184	-0.098	-0.123	-0.119	-0.047	-0.039

The slope PDF (fig.1) was essentially different from the Gaussian one, which indicates strong nonlinearity of surface wave field.

The measured data on wind wave spectra were used for estimation of the short wave spectra and slope probability density function for, which determine radar cross-section in the composite Bragg theory of microwave radar return according to [10].

Microwave measurements were carried out by a coherent Doppler X-band (3.2 cm) scatterometer with the consequent receive of linear polarizations. The observation window was 40x40 cm^2, incidence angle 30, 40, 50, 60 deg, distance from the target was kept 3.16m by selection the height of the antenna aperture from the water, the lid of the working section was made of radio-transparent material (teflon) with the thickness 8 mm.

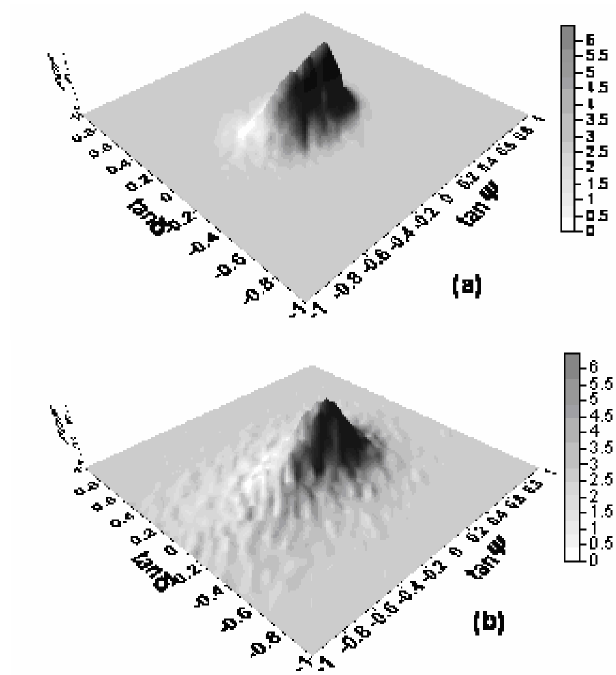

Fig. 1. Slope probability density function (PDF) of large waves . Wind speeds are 12.4 m/s – (a) and 28.7 m/s – (b).

3. RESULTS OF EXPERIMENTS

The dependencies of normalized radar cross-section (NRSC) on 10-m wind speed for 4 incident angles θ=30, 40, 50, 60 for 4 polarizations are shown in fig.2. One can see that the cross-polarized radar return has higher sensitivity to the wind speed for all θ. Although, starting from approximately 20 m/s there is a tendency to saturation in the dependency of cross-polarized NRSC on wind speed, while the co-polarized NRSC shows ambiguous dependence at there wind speeds in close agreement with CMOD5. In fig.2 we compared measured σ_{0PQ} (here P and Q denotes different polarizations and equals to H or V) with the predictions of composite Bragg theory using expressions presented in [9], where the spectral density of surface waves and probability density function for "long waves" were taken from measurements of the wave field. In this configuration of experimental setup the Bragg wave length was λ_b=3.2 cm and cut-off wave length was $3\lambda_b$.

One can see that for co-polarized radar returns the difference with the model is about 2-4 dB for wind speed less than 20 m/s and it can be explained by errors in estimations of the short wave part of the spectrum and insufficient accuracy of calibration. For wind speed exceeding 20-25 m/s the composite Bragg theory fails to predict the observed decline in dependency on the wind speed of co-polarized NRSC, and it means that some non-Bragg mechanisms (short-crested waves, foam, sprays, etc) are responsible for this dependence. For cross-polarized return the difference between the model predictions and experiment is about 10 dB.

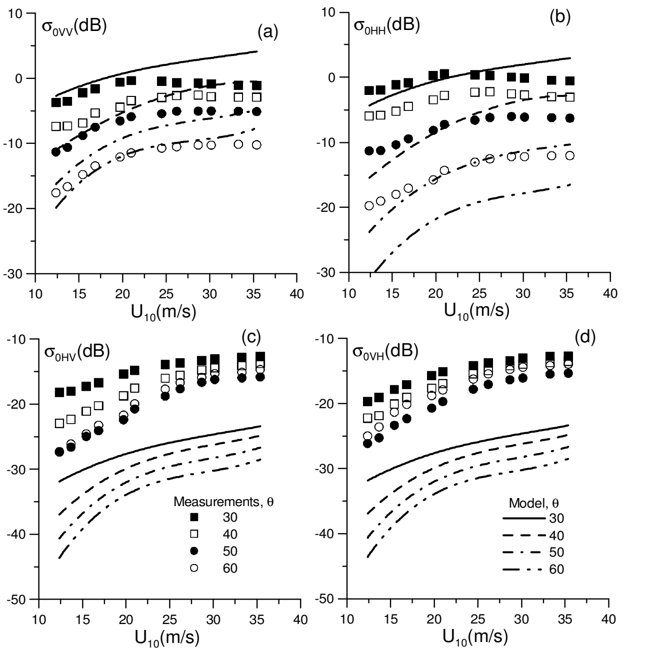

Fig.2 Dependencies of co-polarized and de-polarized NRSC on wind speed for different incident angles. Symbols are experimental data, curves are calculations within composite Bragg theory [10].

Analysis of the Doppler spectra of the return signals provides information about the physical nature of the scattering objects. In fig.3 examples of the Doppler spectra of co-polarized and de-polarized radar return for strong wind U_{10}=30.2 m/s are presented via equivalent velocity of the Bragg scatters: $v = \lambda_0 f / (2\sin\theta)$, where λ_0=3.2 cm is the wavelength of the microwave radiation, f is the Doppler shift of frequency and θ is the incidence angle. It follows from the form of the spectra, that the returned signal is formed by resonant scatters moving with the same velocity exceeding in 20% the phase velocity of the energy containing surface waves independently on the their scale $\lambda_0/(2\sin\theta)$. This kind of scatters can be fragments following the crests of breaking waves.

Basing on obtained dependencies of NRSC on wind speed and incident angle X-band GMF is suggested. Best fit of the data of our experiments gave X-band GMF for upwind azimuth angle. It can be expressed as a composition of two linear fits:

$$\sigma_{0VH}^{X} = \begin{cases} A_0(\theta) + A_1(\theta)U_{10} \text{ for } U_{10} < 22.7\text{m/s}, \\ B_0(\theta) + B_1(\theta)U_{10} \text{ for } 22.7\text{m/s} < U_{10} < 40.0\text{m/s}, \end{cases} \quad (2)$$

with the polynomial approximation for $A_i(\theta) = c_0^i + c_1^i\theta + c_2^i\theta^2$ and $B_i(\theta) = d_0^i + d_1^i\theta + d_2^i\theta^2$. Polynomial coefficients are presented in the Table 2.

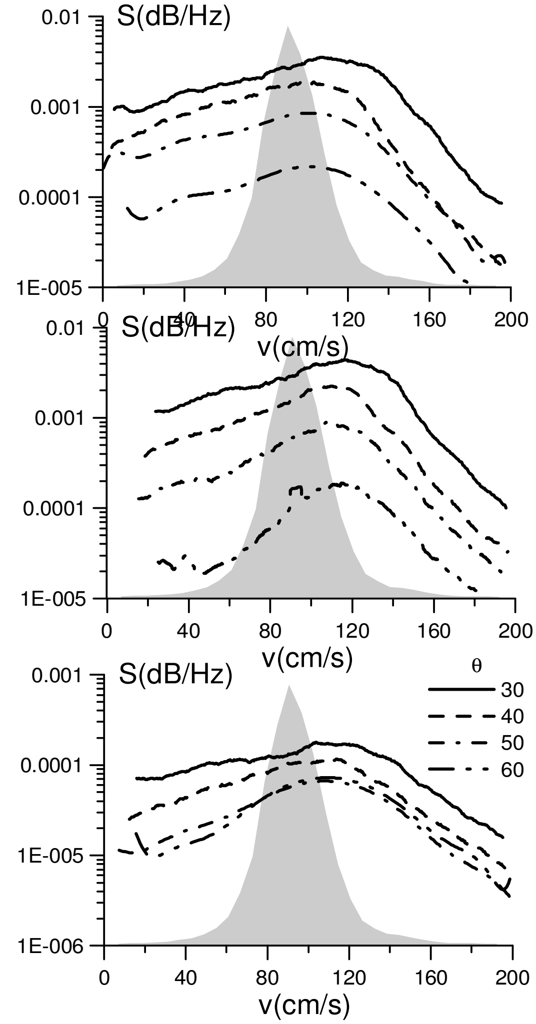

Fig.3 Doppler spectra of co-pol (a-VV, b-HH) and de-pol (c-HV) X-band microwave return at different incidence angles looking upwind plot via equivalent velocity of the Bragg scatters. Grey silhouette is omnidirectional phase velocity spectra of surface waves

Table 2.

	c_0	c_1	c_2		d_0	d_1	d_2
A_0	-0.67	-1.31	0.0105	B_0	-1.37	-0.918	0.0084
A_1	-0.044	0.024	-0.00014	B_1	-0.15	0.0125	-0.000105

Then it seems reasonable to compare the dependence of cross-polarized X-band radar cross-section on 10-m wind speed obtained in laboratory conditions with the similar dependence obtained from the field data for C-band radar cross-section. Using approximation (2) we calculated σ_{VH}

for θ=22.5, 27,5, 32.5, 37.5 like in [2] for U_{10} from 10m/s to 40 m/s and superimposed it in fig.4 with σ_{VH} from RADARSAT-2 dual-polarization SAR vs in situ–measured U_{10} from buoys, SFMR data, and H*Wind taken from fig.1 of [7]. Comparing shows very similar dependencies of σ_{VH} on U10 for both polarizations with the constant bias, then we have for C-band $\sigma_{VH}^{C} = \sigma_{VH}^{X} - 4$.

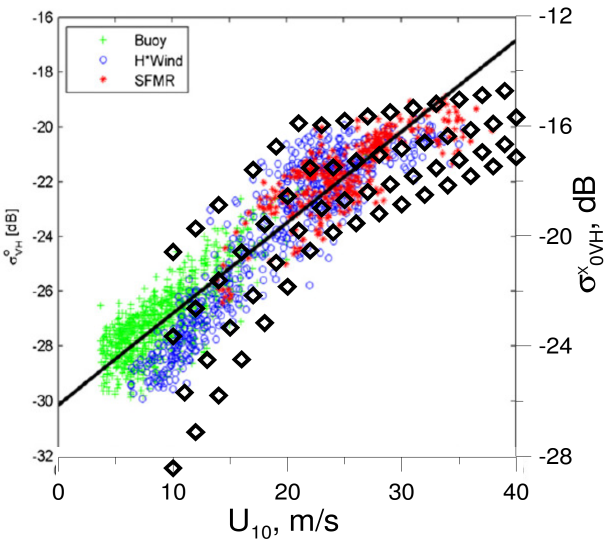

Fig.4 σ_{VH} from RADARSAT-2 dual-polarization SAR vs in situ–measured U10 from buoys, SFMR data, and H*Wind from [7] and superimposed approximation (2) of laboratory data (black diamonds) for θ=22.5, 27,5, 32.5, 37.5.

4. CONCLUSION.

Laboratory experiments aimed for retrieving experimental dependencies of the normalized radar cross-section on wind speed and incident angle was fulfilled. Parameters of air-flow velocity (wind friction velocity and roughness height) and surface wind waves (spectra and probability density function of slopes) in the laboratory facility were measured simultaneously. It was shown that both co-polarized and de-polarized radar return depend on incidence angle, although the de-polarized return is less sensitive. Analysis of the Doppler spectra of the radar backscatter at four polarizations enabled us to conclude that the radar return is formed by resonant scatters moving with the velocity exceeding in 20% the phase velocity of the energy containing surface waves, i.e. a kind of bound waves. Basing on the measurements the X-band and C-band geophysical model functions (GMF) were derived for wind speed from 10 to 40 m/s and incidence angles from 30 to 60 degrees. Examples of hurricane wind speed retrieval with the use of the new GMF are discussed.

5. ACKNOWLEGEMENTS

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