Study of the Doppler Spectrum of the Microwave Radar Signal Backscattered from the Water Surface at Low Incidence Angles in the Presence of a Constant Current: Experiment and Modeling

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Abstract

Measurements of the water surface backscatter at low incidence angles were performed using a Ka-band Doppler radar from the bridge over the Oka river in Nizhny Novgorod in June-October of 2019. Incidence angles varied from nadir to 25° during experiments. In this paper the first results of experimental data processing are presented and the dependency of Doppler frequency shift on incidence angle and an azimuth angle are analyzed. Data acquired in the experiments can be used for validation of theoretical models. The method for the estimation of the velocity of surface current using Doppler central frequency shift is introduced and validated.

1 Introduction

There are a number of methods of measurements of surface currents. The Lagrangian drifters measure surface currents directly [1]. There are not enough drifters to ensure regular measurements of surface currents over the World Ocean. The remote sensing methods are used to measure current velocities. The acoustic Doppler current profiler measure current velocities in water column but have a problem in measuring surface currents [2]. There is a method to measure current velocities using SAR Dual-Beam Interferometry. The existing space-born radars do not use that method but it was validated for plane measurements [3]. The method for current velocity estimation using optical images was introduced in the study [4].

The Doppler spectrum of the signal reflected from the sea surface is more informative than normalized radar cross section. It contains information on the direction of scatterer movement relative to the direction of scanning. Ground-based HF-radars are used for measurements of currents [5]. The radar measures Doppler spectra of the backscattered signal at moderate incidence angles, when the Bragg scattering mechanism dominates. The measurements of the Doppler spectrum central frequency shift at two azimuthal angles are used to retrieve surface current velocity. Analysis of the Doppler information from Sentinel 1 allows retrieving surface current velocity [6]. The planned launch of the Sea surface KInematics Multiscale (SKIM) monitoring project [7] has aroused interest in the Doppler spectrum at low incidence angles. Ka-band radar onboard will operate at incidence angles of 6° and 12°. However, field experiments on DS measurements at low incidence angles have not yet received much attention.

Our group has been studying the Doppler spectrum of the microwave radar signal backscattered from the sea surface at low incidence angles for a few years now. The first measurements of the sea surface backscatter at low incidence angles were performed using Ka-band Doppler radars from the offshore platform in Black Sea in October of 2016. The results were introduced on the previous URSI GASS [8]. Based on those experimental data the sea surface parameters retrieval algorithm using Doppler spectrum measurements at low incidence angles was developed [9]. In this paper the results of the water surface backscatter measurements in the presence of a constant current at low incidence angles are presented and the surface current velocity retrieval algorithm is introduced and validated.

2 Description of the Experiment

Experiments took place on the bridge over the Oka river in Nizhny Novgorod in June-October of 2019. The height of the bridge is 42 m above the water surface. The speed and direction of the wind was measured using WindSonic anemometer that was installed on the bridge. The wind speed measured by anemometer is converted to the wind speed on the height of 10 m in the logarithmic profile approximation [10]

$$U_{10} = \frac{u^*}{0.4} \ln\left(\frac{10}{z_0}\right). \quad (1)$$

The formula is obtained for the case of neutral stratification, where z_0 (in meters) is the surface roughness parameter (elevation). In the calculations, we use the following expression for z_0 [11]:

$$z_0 = \frac{0.000684}{u^*} + 0.428 \cdot u^* - 0.0443, \quad (2)$$

where z_0 and u^* are given in centimeters and centimeters per second, respectively. The waves on the river were recorded by camera throughout all the experiment. The surface current was measured by measuring the speed of the motion of a very light and thin wooden tablet that was carried along the river.

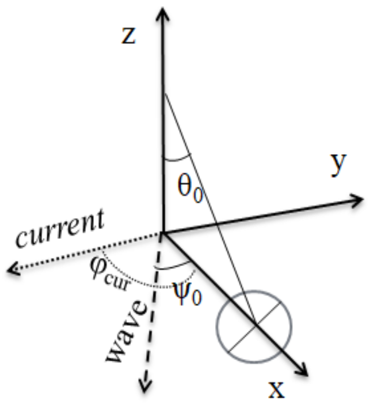

Figure 1. Measurement scheme.

Measurements of the water surface backscatter were performed using the Doppler radar with a symmetrical (6°x6°) antenna beam; radar wavelength is 9.7 mm (30.9 GHz). The rotating apparatus allowed changing azimuth angle by turning around Z axis (see measurement scheme on Fig. 1) and also changing incidence angle in XZ plane. The aperture of radar is oriented vertically downward at an incidence angle θ_0 to the vertical, which changed from 0° to 25°. X axis is pointed in the probing direction. The angle between probing direction and wind direction is ψ_0, the angle between current and probing directions is φ_{cur}. Near the Molitovsky bridge the Oka river flows from the South to the North. The waves are produced by the wind; the current direction coincides with the river flow. During the experiment we changed the azimuth angle from 180 with respect to the North (perpendicular to the bridge, against the flow) to 110 degrees (East of the bridge) and 250 degrees (West of the bridge). The Doppler spectrum (DS) of the backscattered signal was measured. The processing procedure of the experimental data is described in [9].

3 Retrieval of the surface current velocity

3.1 Surface current velocity

According to [12] the surface current leads to an additional frequency shift in the Doppler spectrum. That additional current frequency shift f_C depends on the wavelength of the incidence radiation λ_{em}, incidence angle θ_0, an angle between the probing direction and surface current direction φ^* and the velocity of current U (see Eq. 23 in [12]). So if we measure azimuth dependence of DS shift and calculate DS shift using DS model, the biggest difference between them will be when probing direction and current directions coincide. The formula for the current velocity is

$$U = \frac{f_C \cdot \lambda_{em}}{2\sin(\theta_0)\cos\varphi^*}. \quad (3)$$

3.2 DS model

The main contribution to backscattering at small incidence angles is made by quasi-specular scattering in the facets of the large-scale wave profile perpendicular to the incident radiation. Within the Kirchhoff approximation the DS of the backscattered signal has the Gaussian form

$$S(f) = A_0 exp\left(-\frac{2(f - f_{sh})^2}{(\Delta f)^2}\right). \quad (4)$$

Here f_{sh} is DS shift and Δf is DS width. In [13] the formulas for the DS are derived taking into account the antenna pattern of the radar. The procedure also explained in [9]. The DS shift depends on second-order statistical characteristics of waves.

4 Results

The results of experiment that was conducted on the 3rd of October 2019 since 12:57 till 14:52. The angle between wave direction and the current is 5 degrees. Current velocity according to the measurements was 0.3 m/s.

Figure 2. The scheme of experiment, orange arrows show the probing directions.

There is no swell in the river so the wind direction coincides with the wave direction as it was observed during the experiment. The wave spectrum depends on wind speed and wave fetch. In the experiment wave fetch can be considered 4 km (see the map on Fig.2). Wind speed U_{10} = 5 m/s was constant during the experiment. Dimensionless wave fetch $x_0 = xg/U_{10}^2$, where g = 9.8 m/s^2, x=4000 m, x_0 = 1568. We used spectrum model [14] to calculate the second order statistical parameters and equations 10 from [9] was used to calculate Doppler shift to calculate DS shift without taking into account the current.

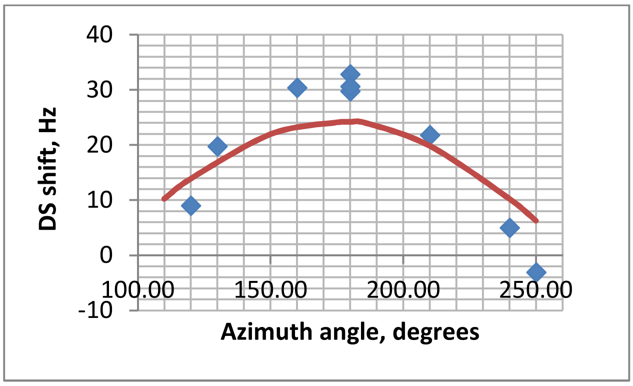

Figure 3. Dependence of the measured and calculated DS shifts on the angle between probing direction and the direction of the current (incidence angle is 7.5 degrees). Blue dots are experimental results, red line is model calculations.

The measured and calculated DS shifts are shown on the Fig. 3 for the incidence angle 7.5 degrees. It can be seen that as an angle between probing direction and the current increases the difference between modeled and measured DS shifts decreases. If we suppose that the difference between modeled DS shift and the measured one defined only by the current we can calculate an additional frequency shift in the Doppler spectrum and use the Eq. 3 to calculate current velocity. The results are presented in the Table 1.

Table 1. Surface current velocity retrieval

time	φ*, degrees	θ_0, degrees	f_{sh}, experiment, Hz	f_{sh}, model, Hz	U, m/s
13:10	180	7.5	33	24	0.33
13:23	180	12.5	55	40	0.34
13:30	180	17.5	78	56	0.37
13:06	150	7.5	22	30	0.35
13:20	150	12.5	36	55	0.46
14:20	150	17.5	51	71	0.36

It can be seen that for small incidence angles (the DS model [13] can be used for θ_0<8-15^0) and small azimuth angles between probing direction and the current (so the additional frequency shift in the Doppler spectrum is different from zero) the DS shift measurements can be used to measure the surface current velocity.

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If you are interested in the experimental data, feel free to contact Maria Ryabkova: m.rjabkova@gmail.com.