URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Doppler Spectrum of the Signal Backscattered at Low Incidence Angles from the River with Constant Current: Model and Experiment

M. Ryabkova*, V. Karaev, M. Panfilova, Yu. Titchenko, Eu. Meshkov, and E. Zuikova
Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia

Abstract

A simple method to calculate the wave spectrum in the presence of the constant river current is presented. The formation of the Doppler spectrum of the microwave radar signal backscattered from the water surface at low incidence angles is modeled. 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 results of comparison of experimental data processing and the model Doppler spectrum are presented. It is shown that the "simple" model that describes the wave spectrum and Doppler spectrum in the presence of the constant current allows to get results that are similar to experimental measurement yet differ especially in the case of sounding along the current. New measurements for different conditions will help to modify the model.

1 Introduction

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 [1]. The planned launch of the Sea surface KInematics Multiscale (SKIM) monitoring project [2] 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 (DS) 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 at URSI GASS 2017 [3]. Based on those experimental data the sea surface parameters retrieval algorithm using Doppler spectrum measurements at low incidence angles was developed [4]. In June-October of 2019 the measurements of the Doppler spectrum on the river were conducted. In the paper [5] 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. It was shown that it is possible to retrieve the velocity of current using the formula for the additional frequency shift in the DS from [6]. The paper [6] does not provide the theory for the full DS form. This paper focuses on the DS of the reflected signal in the case of constant current and comparison with experiment.

2 Wave spectrum in the presence of constant current

We propose the simple model of transformation of the wave spectrum in the presence of current. The velocity of current is considered to be constant over the wave fetch, the wave fetch is small and only wind waves are present on the river. To simplify subsequent transformations, we assume that the axis X is directed in the direction of sounding and, in a particular case (see Fig. 1), against the current.

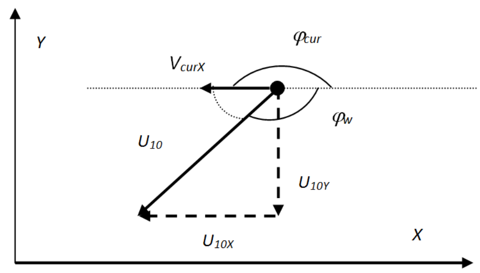

Figure 1. Observation scheme: U_{10} and φ_w - wind speed at a height of 10 m and wind direction, respectively, V_{cur} and φ_{cur} - current speed and direction, respectively.

Let the wind in a stationary coordinate system be directed at an angle, counting from the X-axis. If we switch to a moving coordinate system associated with the current, we get the effective wind speed U_{10eff} and direction φ_{weff}. As a result, the speed and direction of the wind in a "moving" coordinate system associated with the current will differ from the speed and direction of the wind in a stationary coordinate system. The formation of waves in the moving coordinate system will occur under the influence of the effective wind. The difference in wave parameters will be maximum for upstream and downstream winds.

The spectrum model [7] that we use for modeling has three parameters: wind speed U_{10}, dimensionless wave fetch $x=Xg/U_{10}^2$ (X-wave fetch in meters, g - acceleration of gravity) and wave direction. If we calculate the wave spectrum in a "moving" coordinate system we will use the effective wind speed and direction in calculations.

In the calculations (Fig.2) , the variable parameter was the wind direction in a fixed coordinate system with the same direction and speed of the current (φ_{cur} = 180°).

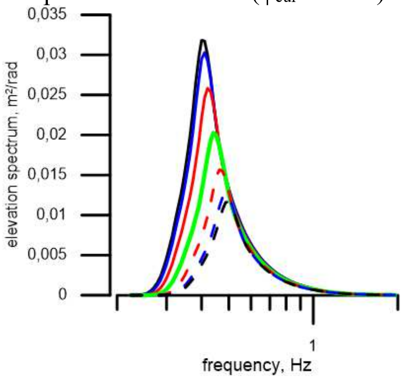

Figure 2. Elevation spectra for wind speed = 5 m/s, dimensionless fetch 4000, current speed 0.5 m/s, and current direction = 180° for wind directions: 0°, 30°, 90°, 120°, 150° and 180°.

The dependence observed in the Fig.2 is expected: the "relative" wind speed is maximal in the opposite direction of the wind speed (the spectrum is shifted more strongly to the region of small frequencies) and is minimal in the passing direction.

When we go back to the fixed coordinate system we will have to take into account the fact that frequency depends on the speed of current and the angle between the wave and current directions. The relationship between frequency and wavenumber for water waves is determined by the dispersion relation ω=Ω(k), therefore frequency in the unmoving coordinate system:

$$\omega_0 = \Omega(k) + \vec{k}\vec{V}_{cur}. \quad (1)$$

The function $\omega_0(k)$ crosses zero one or two times depending on the speed of current (see Fig. 3). The resulting wave spectrum in the unmoving coordinate system is shown in Fig.4. It can be seen that the form of the spectrum depends on the angle between wave and current.

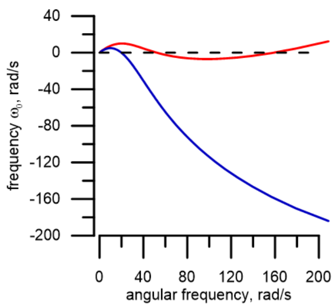

Figure 3. Dependence of the angular frequency with the current on the frequency without the current: red curve – velocity of current is 0.25 m /s and blue curve – 0.5 m /s.

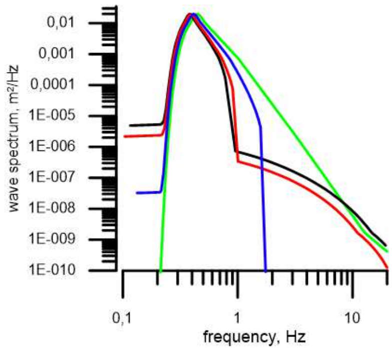

Figure 4. Frequency spectrum of heights for wind speed = 5 m/s, dimensionless fetch 4000, current speed 0.5 m/s, current direction φ_{cur} = 180 ° and wave propagation directions φ_w: 0 ° - black curve, 30 ° - red curve, 60 ° - blue curve and 90 ° - green curve.

3 Doppler spectrum in the presence of constant current

The Doppler spectrum (DS) model includes the statistical parameters of the wave and the characteristics of the antenna radiation pattern [4, 8]. Therefore, to DS model it is necessary to calculate the second statistical moments for the wave formed on the current in a fixed coordinate system associated with the radar.

The influence of the current will affect those statistical moments where the frequency is included, such as the variance of the vertical component of the orbital velocity, variance of slopes and the coefficient of correlation between them.

To calculate the Doppler spectrum we will use the model that was discussed in the papers [4, 8]. We will analyze the dependence of the width and shift of the Doppler spectrum on the azimuth angle for two velocities of current. In Fig.5 red curve corresponds to velocity of current 0.25 m/s, blue curve – 0.5 m/s, black curve – no current.

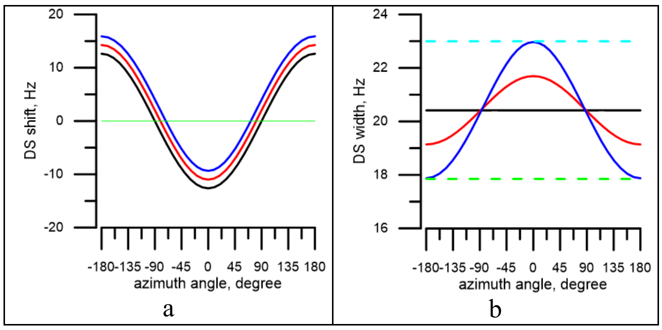

Figure 5. The dependence of the shift (a) and width (b) of the Doppler spectrum on the angle between the direction of the current and the direction of the wave (wind). The sensing direction is 180°, the angle of incidence is 7°.

From the model estimates, it follows that in the direction of wave propagation at an angle of 90° degrees in the absence of current, the DS shift is zero. In the presence of a current, there is a "shift" of the position of the zero offset of the Doppler spectrum, and it is greater the higher the current velocity (see the intersection of the green line in Figure 5a). As a result, the distance between the "zeros" is less than 180°, i.e. the azimuthal dependence becomes asymmetric.

To assess the influence of the wave transformation effect on the current, calculations were performed for wind speeds of 4.5 m/s and 5.5 m/s for the case of no current, which corresponds to the limits of the change in the effective wind speed. In Figure 5b, the limits of change are shown in light blue (5.5 m/s) and green (4.5 m/s) lines. When the direction of the current changes, the width of the Doppler spectrum changes and reaches its maximum value when the wave propagates towards the current. This is due to changes in the effective wind speed and the effective propagation direction, which determine the values of the statistical moments used to calculate the Doppler spectrum.

4 Comparison with the experiment

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

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

Here f_{sh} is DS shift and Δf is DS width. In [8] the formulas for the DS are derived taking into account the antenna pattern of the radar. The data processing procedure is explained in [4].

Let's consider the solution of the direct problem, i.e. using the information about the wind speed and direction, the length of the wind acceleration, the speed and direction of the current, the direction of sounding and the angle of incidence, we calculate the DS and compare it with the measured one.

The experiment 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 0.3-0.35 m/s, it was measured using videotape. In the experiment wave fetch can be considered 3644 m (see the map on Fig.2 in [5]), so the dimensionless wave fetch is x=1430, wind speed = 5 m/s.

Further calculations are performed for three cases:

1) the wind speed is 5 m/s, the wind direction is 180, the current speed is 0.35 m / s and the current direction is 180;

2) wind speed is 5 m/s, wind direction is 180 and no current;

3) wind speed is 4.65 m/s, wind direction is 180 and no current.

In the latter case, we assume that the current velocity has reduced the wind velocity relative to the water surface, but the current velocity is not explicitly used in the future.

For each entry, we will denote options 1-3: "1C", " 2C " and "3C".

Figure 6 shows the azimuthal dependence of the shift (a) and width (b) of the Doppler spectrum. The asterisks show the experimental data. The red curve is "1C", the black dotted curve is "2C", and the blue curve is "3C".

The figure shows that the change in wind speed ("2C "and" 3C") does not significantly affect the DS shift, but leads to noticeable changes in the width of the Doppler spectrum. At the maximum values of the azimuth angle (sensing direction), the Doppler spectrum shift approaches the measured values.

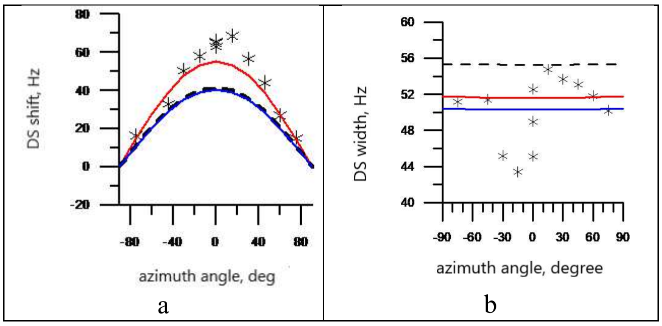

Figure 6. Azimuthal dependence of the displacement (a) and width (b) of the Doppler spectrum. Asterisks - experiment, C1-red curve, C2-black dotted line and C3-blue curve.

From comparing the integral characteristics, we proceed to comparing the shape of the Doppler spectra. Figure 7 shows the Doppler spectra measured at the sensing direction of 0 deg. (a) and 75 deg. (b).

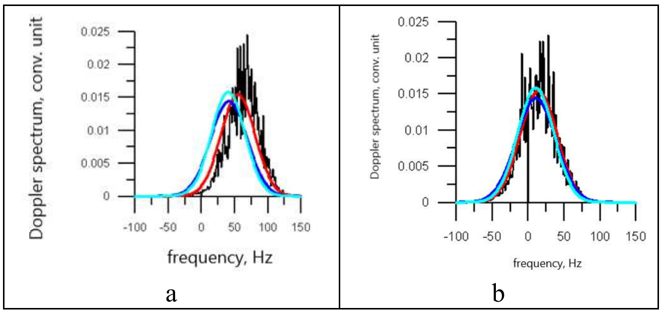

Figure 7. Doppler spectra measured at an angle of incidence of 12.4 deg., and the sensing direction of 0 deg. (a) and 75 deg. (b). The red curve is "1C", the blue curve is "2C", and the blue curve is "3C".

For ease of comparison, all the spectra were normalized to the power (the integral of the Doppler spectrum). The figure shows that the model Doppler spectrum describes well the frequency range of the Doppler spectrum (width) and the shift at the sensing direction of 75 deg, while when probing towards the current, a significant excess of the power spectral density at the "central" frequencies is observed and experiment and model vary significantly.

5 Discussion

It is shown in Fig. 7 that an increase in the shift of the Doppler spectrum of the reflected radar signal during the current does not occur due to the appearance of "new" frequencies in the spectrum (faster scatterers), but due to an increase in the power of the existing scatterers.

There can be two factors coursing this effect. The wave profile changes along the current, i.e. the forward slope, which is moving towards the radar, becomes steeper, and the rear slope is more gentle, and with oblique sounding, the reflected signal power increases for the orbital velocities moving toward the radar. From a formal point of view, in the Doppler spectrum model, the displacement depends on the correlation coefficient between the slopes and the orbital velocities. Distortion of the wave profile leads to an increase in the correlation coefficient and an increase in the displacement of the Doppler spectrum. The second reason is related to the strengthening of the wave collapse process due to the flow in the propagation process. The collapse leads to an increase in the power of the reflected signal during this event. The collapses are "tied" to the crests of the waves, which have a maximum horizontal speed of movement.

Thus, both factors are related to the fact that there is an increase in the areas of the wave profile that have the maximum horizontal component of the orbital velocity and this leads to an additional shift in the Doppler spectrum, due to the" redistribution " of the weight of the spectral components due to the flow. New faster diffusers do not appear, i.e. all the "reflectors" existed, but there was a process of "redistribution" of power between them.

More experiments are needed to understand how different factors influence the reflected signal and how the model can be transformed so it could correctly describe experimental results. New experiment were conducted on the two bridges over Oka river in Nizhny Novgorod in 2020, the processing of the experimental data is ongoing.

6 Acknowledgements

This work is supported by the Russian Foundation for Basic Research (grant 20-05-00462-a) and the grant from the President of the Russian Federation for young scientists MK-1130.2020.5.

7 References

1. Y. Miao, X. Dong, Q. Bao, and D. Zhu, “Perspective of a Ku-Ka Dual-Frequency Scatterometer for Simultaneous Wide-Swath Ocean Surface Wind and Current Measurement,” *Remote Sensing*, **10**, 7, July 2018, doi: 10.3390/rs10071042.

2. R. Fjørtoft, J.-M. Gaudin, N. Pourthie, and C. Lion, “KaRIn - the Ka-band radar interferometer on SWOT: Measurement principle, processing and data specificities,” Proceedings of IGARSS’2010, pp.4823 – 4826.

3. M. S. Ryabkova, V. Y. Karaev, Y. A. Titchenko, and E. M. Meshkov, “Experimental study of the microwave radar Doppler spectrum backscattered from the sea surface at low incidence angles,” Proceedings URSI GASS 2017, pp. 1-4, doi: 10.23919/URSIGASS.2017.8105008.

4. M. Panfilova, M. Ryabkova, V. Karaev, and E. Skiba “Retrieval of the Statistical Characteristics of Wind Waves From the Width and Shift of the Doppler Spectrum of the Backscattered Microwave Signal at Low Incidence Angles,” *IEEE Transactions on Geoscience and Remote Sensing*, Early Access, December 2019, pp. 1-7, doi: 10.1109/TGRS.2019.2955546.

5. M. Ryabkova, V. Karaev, M. Panfilova, Y. Titchenko, E. Meshkov and E. Zuikova, "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," Proceedings URSI GASS 2020, pp. 1-4, doi: 10.23919/URSIGASS49373.2020.9232433.

6. F. Nouguier, B. Chapron, F. Collard, A.A. Mouche, N. Rascle, F. Ardhuin, and X. Wu “Sea Surface Kinematics From Near-Nadir Radar Measurements,” *IEEE Transactions on Geoscience and Remote Sensing*, **56**, 10, October 2018, pp. 6169-6179, doi: 10.1109/TGRS.2018.2833200.

7. M. Ryabkova, V. Karaev, J. Guo, and Yu. Titchenko, “A review of wave spectrum models as applied to the problem of radar probing of the sea surface,” *Journal of Geophysical Research: Oceans*, **124**, October 2019, pp. 7104–7134, doi: 10.1029/2018JC014804.

8. Karaev, V.Yu., Titchenko, Yu.A., Meshkov, E.M., Panfilova, M.A., Ryabkova, M.S. Doppler spectrum of microwave signal backscattered by sea surface at small incidence angles (2019) Sovremennye Problemy Distantsionnogo Zondirovaniya Zemli iz Kosmosa, 16 (6), pp. 221-234;

8 P. S.

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