Measurements of the Sea Surface Waves Parameters and the Doppler Spectrum of the Reflected Signal Using Optical and Acoustic Remote Sensing Methods

M. Ryabkova*, V. Titov, Yu. Titchenko, Eu. Meshkov, V. Karaev, A. Yablokov, K.Ponur, R. Belyaev and M. Panfilova
Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, Russia

Abstract

Active and passive remote sensing techniques can be used simultaneously and their results complete each other. This paper introduces the results of the experiment that took place in October 2019 on the offshore platform in the Black Sea. Two unique pieces of equipment developed in the Institute of Applied Physics were used in the experiment: set of original optical devices for recording of range – time – intensity (RTI) images of sea surface and an underwater acoustic wave gauge. The devices were installed close to each other, optical devices were measuring slope spectrum, acoustic wave gauge can measure significant wave height and variance of slopes of the large-scale (in comparison with the wavelength of the incidence acoustic wave) waves, also the Doppler spectrum of the reflected signal can be measured. The string wave gauge is working on the platform constantly and provides measurements of the omnidirectional spectrum.

1 Introduction

An acoustical wave gauge was developed in the Institute of Applied Physics RAS for surface wave measurement. A number of experiments were conducted using this instrument [1, 2]. An acoustic wave gauge can measure Doppler spectrum of the reflected signal and it also scans the sea surface using ultrasonic pulses. An acoustic wave gauge measurements can be used for satellite measurements validation. In [3] a theoretical description of pulse reflected from the water surface is presented. It is shown, that the form of the reflected pulse depends on significant wave height (SWH) and slope variance. In this paper the method for SWH and slope variance retrieval from ultrasonic pulse measurement is introduced. Also the way to calculate slope variance using elevation spectrum measured by the string wave gauge and the method of using the optical RTI images (range-time-intensity) for the slope spectrum measurements [4,5] are discussed.

2 Description of the Experiment and Equipment

2.1 Test site

Experiment took place on the offshore platform of the Black Sea Gydrophysics Facility near the Katsiveli settlement. Platform is located approximately 500 m to the south from the shore in the open sea; the sea depth at the platform location is 28 m. The optical instruments stood on the south side of the platform; they were fixed at a height of 15 m above the sea surface. The acoustic wave gauge was installed underwater at the depth of 28 m. The string wave gauge is installed on the east corner of the platform. The speed and direction of the wind at a height of 30 m were measured simultaneously.

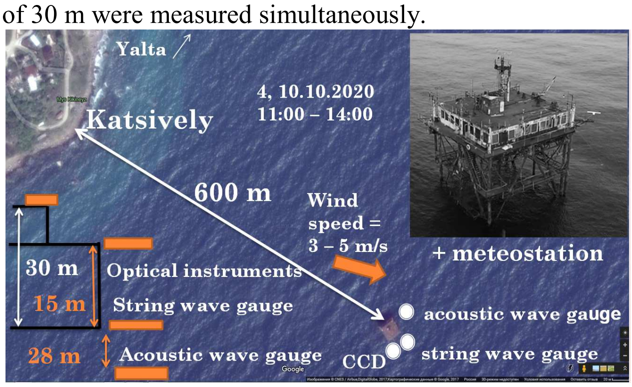

Figure 1. Offshore platform in the Black Sea and the device location.

2.2 Optical instruments

Kinematics characteristics of long surface waves are determined from 2D image of space-time wave slopes (RTI images of sea surface in coordinates range – time – intensity of surface), constructed from optical profiles of sea surface. This RTI images are the optical analogs of images derived from side-looking radars and from the other devices with analogous principles of images formation but having some flexibility depending of needed spatial resolution: it is possible to form RTI images with various range from tens meters to kilometers. The optical device for creating of 2D optical images of space-time wave slopes based on linear array of CCD (Charge-coupled device) photodiodes placed in focal plane of the lens was developed. This device after installing on the sea platform registers the optical profiles of sea surface ranging from some tens meters away of place of installing to horizon and part of the sky.
Two such devices were installed on the platform in order to record two optical RTI images for various directions of observation. Two this images permit to receive whole information about kinematics characteristics of sea surface waves regardless the dispersion relation and on

the other hand to display all waves with various directions of traveling having on the sea surface, because optical contrast of surface waves decreasing with increasing of the angle between directions of observation and wave traveling.

Figure 2. CCD at work.

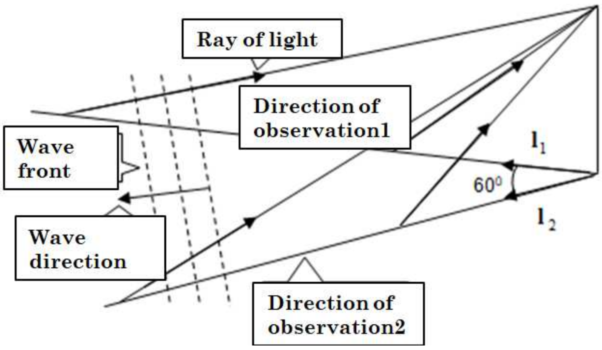

Figure 3. Scheme for observing the sea surface.

2.3 Acoustic wave gauge

The underwater acoustic wave gauge is equipped with pulse and Doppler sonars. The receiving and transmitting antenna of the pulse sonar are oriented vertically upwards on the sea surface, the Doppler sonar antenna is deflected by 5 degrees from the direction to the Zenith.

The wave gauge has a frequency of 200 kHz. The antenna pattern is wide (15°x15°) for both pulse and Doppler channels. Doppler spectrum is measured continuously for 15 minutes, in pulse regime the wave gauge emits 10500 pulses in 15 minutes, pulse length is 40 µs, repetition rate is 15 Hz.

Figure 4. Acoustic wave gauge before the installation.

3 Optical measurements

RTI images enable one to receive complete information about kinematics characteristic of various manifestations on the sea surface, including sea surface waves, near surface wind flow manifestations on the sea surface, internal waves (IW) manifestations, oil slicks and so on owing to its ability to screen objects according to their velocity. A method for retrieval of sea wave's slopes from RTI images is presented.

The principle of wave slopes retrieval is that: we form in each point of the sea surface the dimensionless signal (the relative fluctuations of the sea surface radiance). Figure 5 shows the restored RTI image of the sea surface in radians in gray scale. Figure 6 shows two dimensional spectra of Figure 5. In is possible to show that the spectra will be distributed along the dispersion curve ω^2=gk. One can see the spectra of long surface wave, wind waves and group structure of long wave. Figure 7 shows the wave's slope spectra calculated along the parabolic dispersion curve on the Fig. 6.

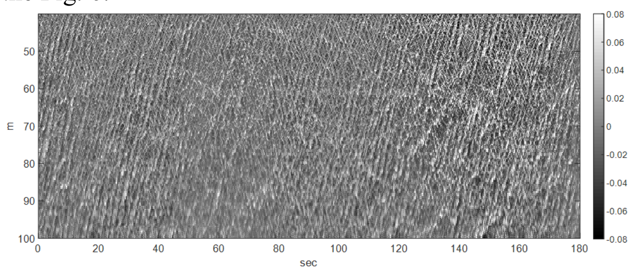

Figure 5. The RTI image of the sea surface. The inset to the right is the wave slopes in radians in gray scale.

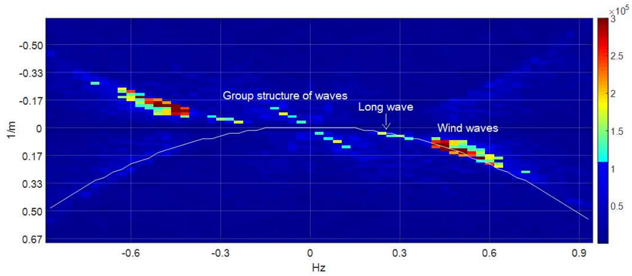

Figure 6. Two dimensional spectra of the RTI image.

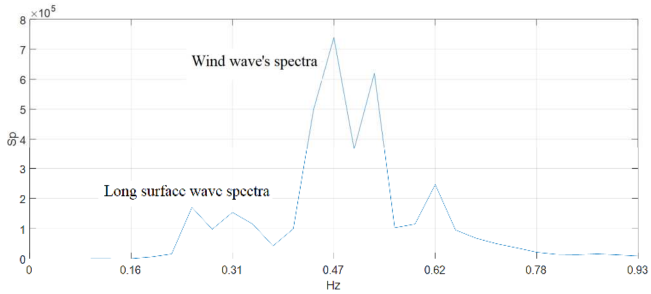

Figure 7. The wave's slope spectra calculated along the parabolic dispersion curve on the Fig. 6.

4 Acoustic measurements

In [3] a theoretical description of pulse reflected from the water surface is presented. It is shown, that the form of the reflected pulse depends on significant wave height (SWH) and slope variance. The dependence of the shape of the reflected pulse on the SWH is shown on Fig. 8.

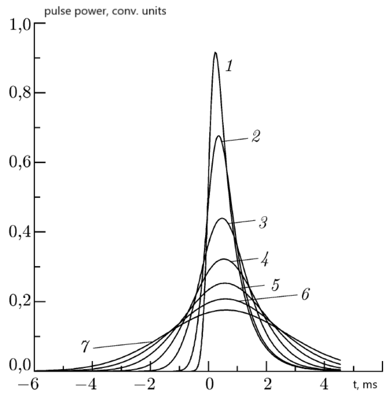

Figure 8. The dependence of the shape of the reflected pulse on the height of a significant wave according to theory from [3] . Curve 1 corresponds to the wave height of 0.5 m, curve 2 – 1 m, curve 3 – 2 m, curve 4 – 3 m, curve 5 – 4 m, curve 6 – 5 m, curve 7 – 6 m. Immersion depth of the emitter 50 m, slope dispersion 0.012 and 0.018, antenna pattern width 30°.

In pulse regime the wave gauge emits 10500 pulses in 15 minutes. The SWH and slope variance are the parameters of the model pulse and they can be selected by finding a model pulse that is close to the average measured pulse (see Fig.9).

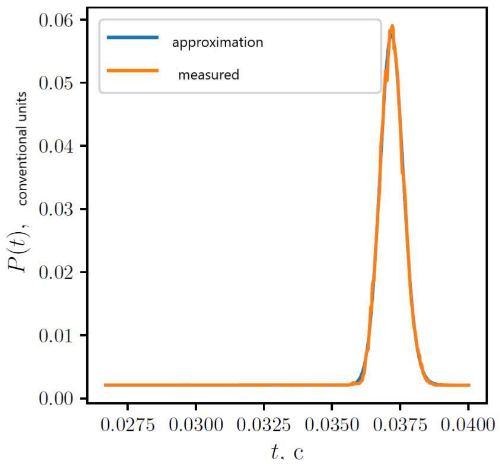

Figure 9. Measured average pulse and approximation.

The string wave gauge was measuring omnidirectional spectrum simultaneously. We can calculate SWH and slope variance from those measurements. There is a problem with calculating slope variance, because string wave gauge can measure the spectrum up to 1 Hz, and we need to know the spectrum of short waves to calculate the slope variance.
The spectrum can be extended to the high frequency range using model spectrum. The model spectrum [6] was used for calculations. The resulting spectrum is shown in Fig. 9.

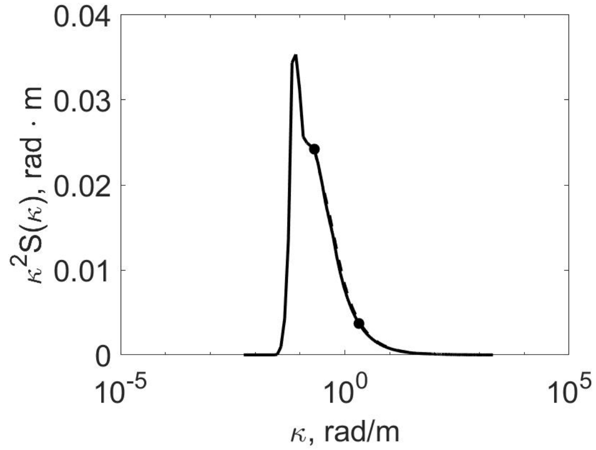

Figure 9. Slope spectrum measured by the string wave gauge extended to the high wavenumber range.

In Table 1 SWH calculated by integrating the wave spectrum measured by the string wave gauge and SWH retrieved from average pulse form analysis are presented. It can be seen that the results are close to each other.

Table 1. SWH, 4th of October, 2019

Time, s	String wave gauge, SWH, m	Acoustic wave gauge, SWH, m
9:16	0.34	0.36
9:51	0.38	0.36
10:26	0.39	0.37
11:01	0.41	0.35
11:36	0.41	0.36

In [7] theoretical description of the Doppler spectrum (DS) of the microwave signal reflected from the water surface at small incidence angles is introduced. It is shown in case of near-nadir sounding within the Kirchhoff approximation the Doppler spectrum of the backscattered signal has the Gaussian form

$$S(f) = A_0 exp\left(-\frac{2(f - f_{sh})^2}{(\Delta f)^2}\right). \qquad (1)$$

Here f_{sh} is DS shift and Δf is DS width, A_0 is the amplitude. The parameters of the Doppler spectrum depend on the antenna pattern and the parameters of waves, such as slope variance, variance of the vertical component of the orbital velocity and the coefficients of correlation between them. Those wave parameters theoretically described as integrals of the wave spectrum.
Doppler spectrum can be calculated using theoretical formulas from [7]. In Fig. 10 the theoretical and measured Doppler spectrum are presented.

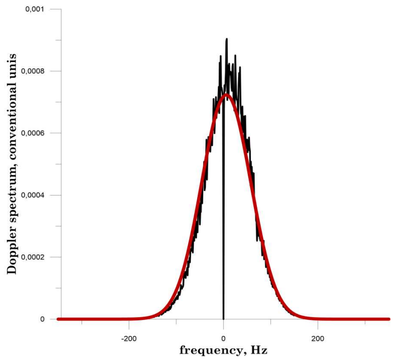

Figure 10. Doppler spectrum measured by the acoustic wave gauge (black) and model Doppler spectrum (red).

It can be seen that experiment and model are in agreement with each other.

5 Conclusion

Optical measurements of the slope spectrum based on the analysis of the RTI images of sea surface in coordinates range – time – intensity of surface can be used to retrieve the slope spectrum. Slope variance can be retrieved from average pulse form analysis; it can also be calculated by integrating the wave spectrum measured by the string wave gauge. The significant wave heights measured using acoustic and string wave gauges are close. Model Doppler spectrum based on the Kirchhoff approximation is correct in the case of probing at small incidence angles. In the future, it is planned to compare the wave spectra obtained by different methods based on acoustic measurements, optical measurements, and contact measurements of a string wave gauge.

6 Acknowledgements

Authors express their gratitude to the Black Sea Gydrophysics Facility for the access to the platform, meteorological and wave spectrum data. This work is supported by the Russian Foundation for Basic Research (grant and 19-05-00547 a) the grant from the President of the Russian Federation for young scientists MK-1130.2020.5.

7 References

1. Y.A. Titchenko, G.A. Baydakov, V.Y. Karaev, M.S. Ryabkova, and M.A. Panfilova, "The use of underwater sonar at small angles of incidence for in-situ measurements of sea surface parameters", Proceedings 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), 2017, pp. 2850-2856, doi: 10.1109/PIERS-FALL.2017.8293620.

2. M. Ryabkova, E. Meshkov, V. Karaev, and M. Panfilova, "Undewater Acoustic Wave Gauge Measurements of Sea Wave Parameters: Test Experiment and Modeling," Proceedings IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, August 2019, pp. 8113-8116, doi: 10.1109/IGARSS.2019.8900640.

3. Karaev, V.Y., Meshkov, M.E. & Titchenko, Y.L. Underwater Acoustic Altimeter. *Radiophys Quantum El* 57, 488–497 (2014). https://doi.org/10.1007/s11141-014-9531-8

4. V.V. Bakhanov, A.A. Demakova, A.E. Korinenko, M.S. Ryabkova, and V.I. Titov, "Estimation of the wind Wave spectra with centimeters-to-meter lengths by the sea surface images" *Physical Oceanography*, **25** ,3, 2018, pp. 177-190, doi: 10.22449/1573-160X-2018-3-177-190.

5. V. Titov; V. Bakhanov; A. Demakova; I. Sergievskaya; A. Kuzmin; I. Sadovsky; D. Sazonov. "Investigation of short-scale sea wave spectra with optical and radiometric methods". Proceedings Volume 11150, Remote Sensing of the Ocean, Sea Ice, Coastal Waters, and Large Water Regions 2019; 111501P (2019) https://doi.org/10.1117/12.2533316

6. 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.

7. 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.