Active and Passive Remote Sensing Measurements of the Sea Surface Waves

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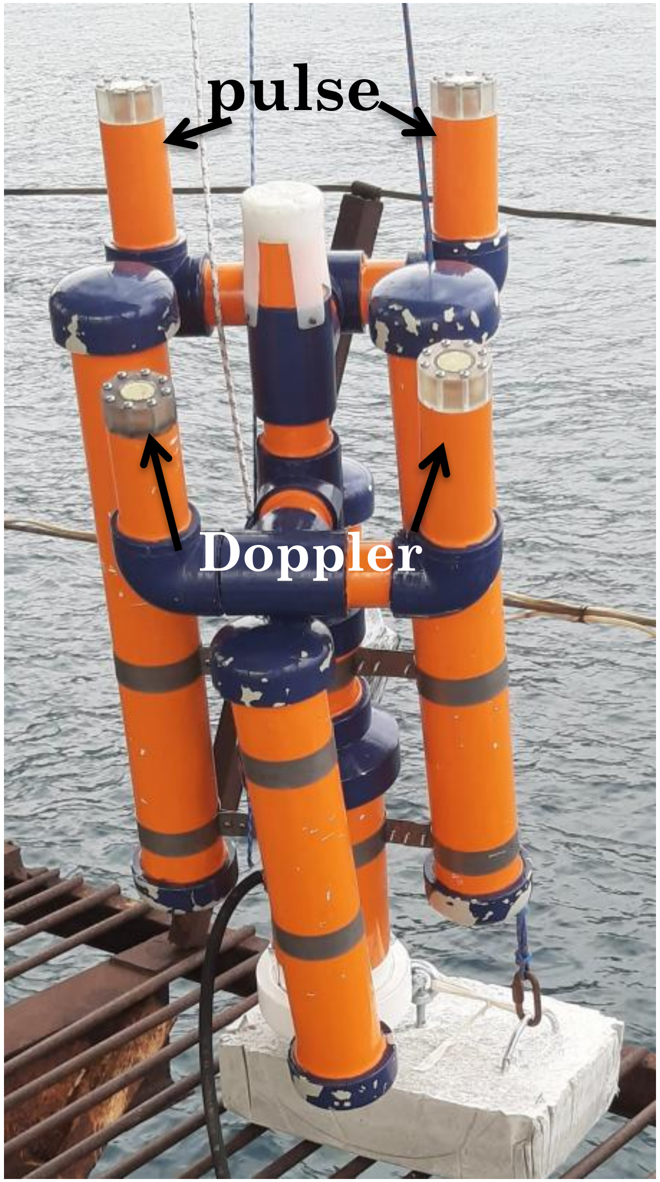
Acoustic wave gauge



The 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.
Pulse sonar emits pulses of 5 to 40 microseconds in length with a repetition rate of 15 to 100 Hz.
Wave gauge uses ultrasound at frequency 200 kHz. It can measure

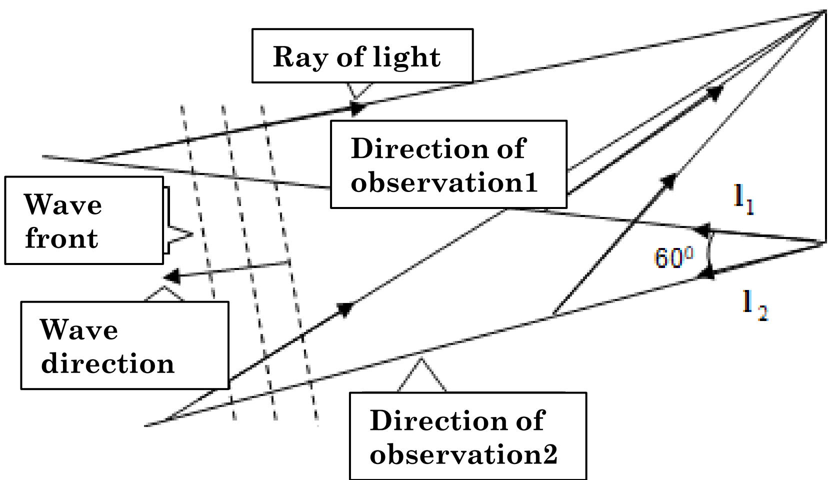
- significant wave height
- Doppler spectrum of the reflected signal

Acoustic wave gauge was made by Roman Belyaev at IAP RAS

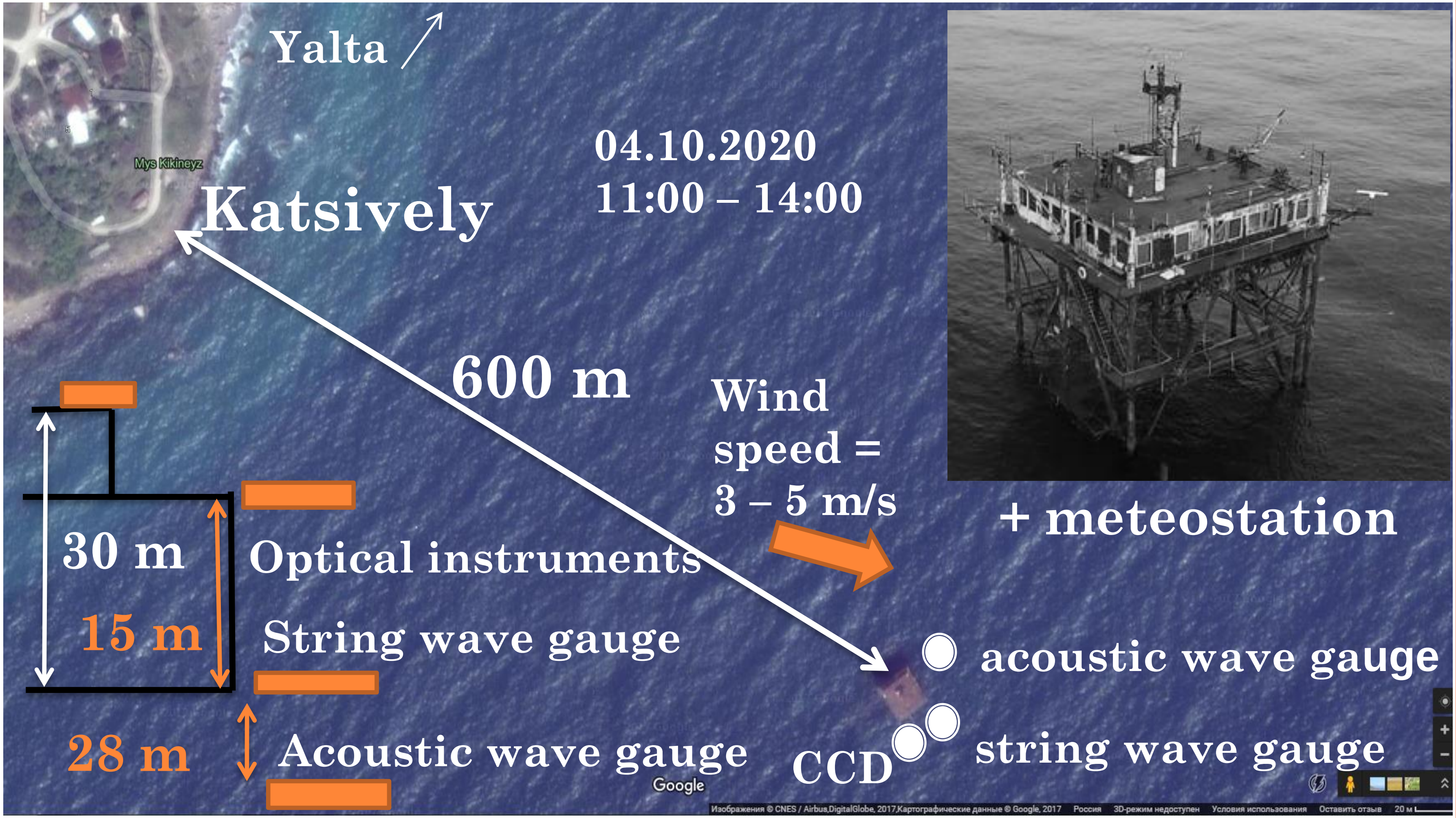
CCD

A method for constructing large - scale space – time images of the sea surface in time-space coordinates has been developed. Images are constructed on the optical cross sections of the sea surface at grazing incidence angles. An optical device based on the lines of CCD photodiodes was created. The main mechanism that determines the visibility of objects on the surface (waves, slicks, wind flow manifestations) at sliding viewing angles is the shading of wave slopes. Two images with different viewing directions allow to get complete information about the kinematic characteristics of long waves.

Scheme for observing the sea surface



Experiment. August – October 2019



An oceanographic platform of the Marine Hydrophisical Institute near the Katsiveli settlement in Crimea

ACOUSTIC PULSE MEASUREMENTS

Recording time =15 minutes

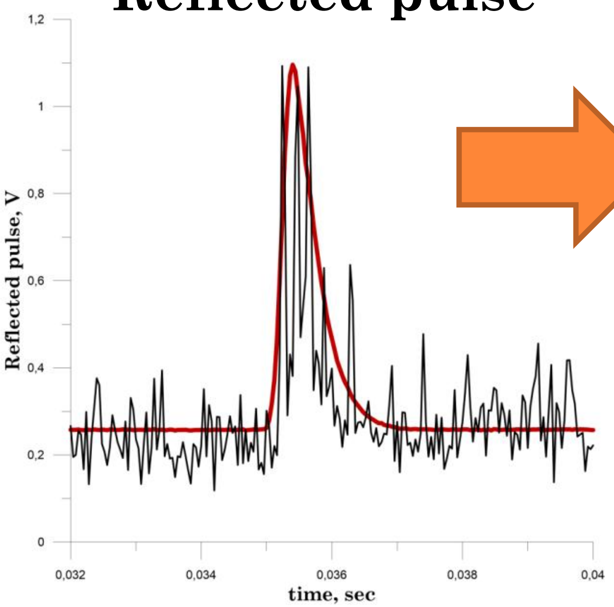
Number of pulses = 10509

Pulse repetition rate = 15 Hz

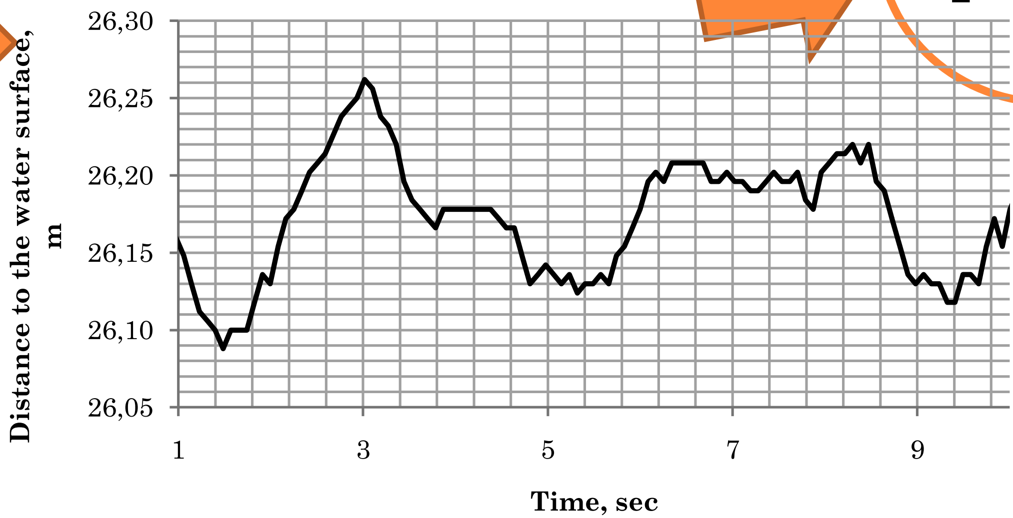
Pulse length = 40 microseconds

Frequency = 200 kHz (wave length = 8 mm)

Reflected pulse

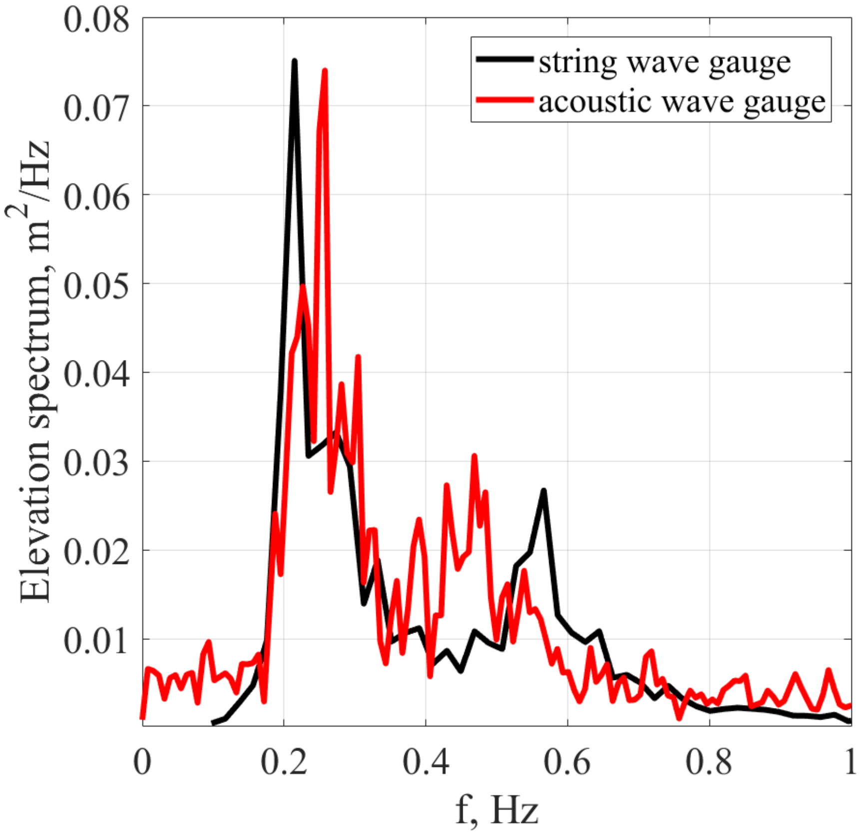


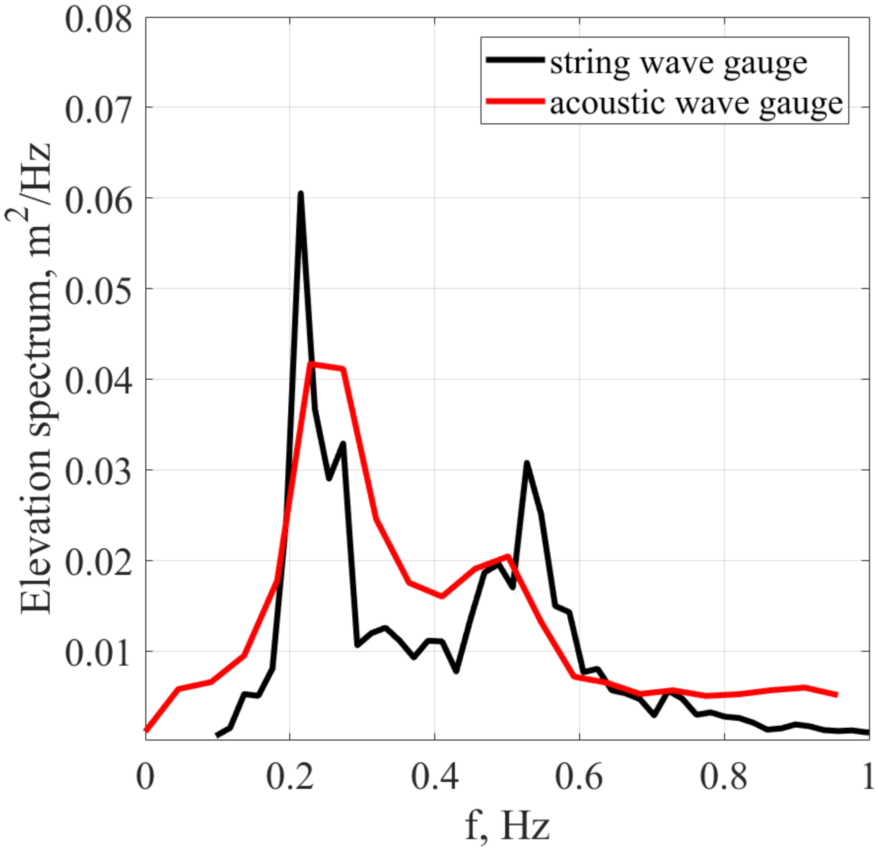
Distance from the gauge to the water surface



Wave Spectrum

Spectrum





String wave gauge 11:01 – 11:21 11:41 – 12:01

Acoustic wave gauge 11:01-11:16 11:36 – 11:51

$H_s^{string} = 0.41m$ $H_s^{acoustic} = 0.44m$ $H_s^{string} = 0.40m$ $H_s^{acoustic} = 0.45m$

DS at low incidence angles (model)

$$\Delta f \propto \frac{\cos\theta_0}{\lambda}\sqrt{\sigma_{tt}^2 - \frac{11.04\cdot(K_{xt})^2}{\delta_x^2 + 11.04\cdot\sigma_{xx}^2} - \frac{11.04\cdot\cos^2\theta\cdot(K_{yt})^2}{\delta_y^2 + 11.04\cdot\sigma_{yy}^2}}$$

DS width

$$f_{sh} = -\frac{2\cdot\sin\theta_0}{\lambda}\cdot\frac{11.04\cdot K_{xt}}{\delta_x^2 + 11.04\cdot\sigma_{xx}^2}$$

DS shift

$$\sigma_0 \cong \frac{|R_{eff}(U_{10})|^2 \exp\left[-\frac{\mathrm{tg}^2\theta_0}{2}\left(\frac{11.04}{\delta_x^2 + 11.04\sigma_{xx}^2}\right)\right]}{2\cos^4\theta_0\sqrt{\left(\frac{\delta_x^2}{11.04} + \sigma_{xx}^2\right)\left(\frac{\delta_y^2}{11.04\cos^2\theta_0} + \sigma_{yy}^2\right)}}$$

RCS

Y. A. Titchenko and V. Y. Karaev, *Radiophysics and Quantum Electronics, vol. 55, pp. 493-501, 2013.*

Second-order statistical characteristics

$$\sigma_{xx}^2 = \int_0^{2\pi} \int_0^{\kappa_b} W(\kappa,\phi)\kappa^3 \cos^2(\phi)\, d\phi\, d\kappa,$$

$$\sigma_{yy}^2 = \int_0^{2\pi} \int_0^{\kappa_b} W(\kappa,\phi)\kappa^3 \sin^2(\phi)\, d\phi\, d\kappa,$$

mean square slopes

$$\sigma_{tt}^2 = \int_0^{2\pi} \int_0^{\kappa_b} W(\kappa,\phi)\kappa\omega^2(\kappa)\, d\phi\, d\kappa,$$

orbital velocity

$$K_{xt} = \int_0^{2\pi} \int_0^{\kappa_b} W(\kappa,\phi)\kappa^2\omega(\kappa) \cos(\phi)\, d\phi\, d\kappa,$$

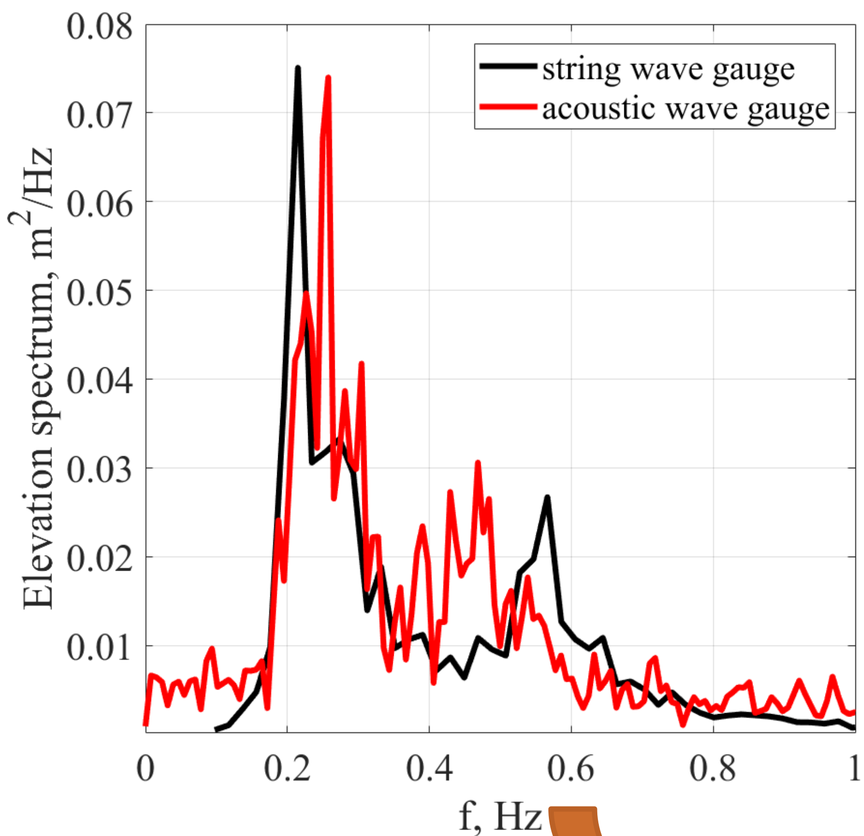
$$K_{yt} = \int_0^{2\pi} \int_0^{\kappa_b} W(\kappa,\phi)\kappa^2\omega(\kappa) \sin(\phi)\, d\phi\, d\kappa,$$

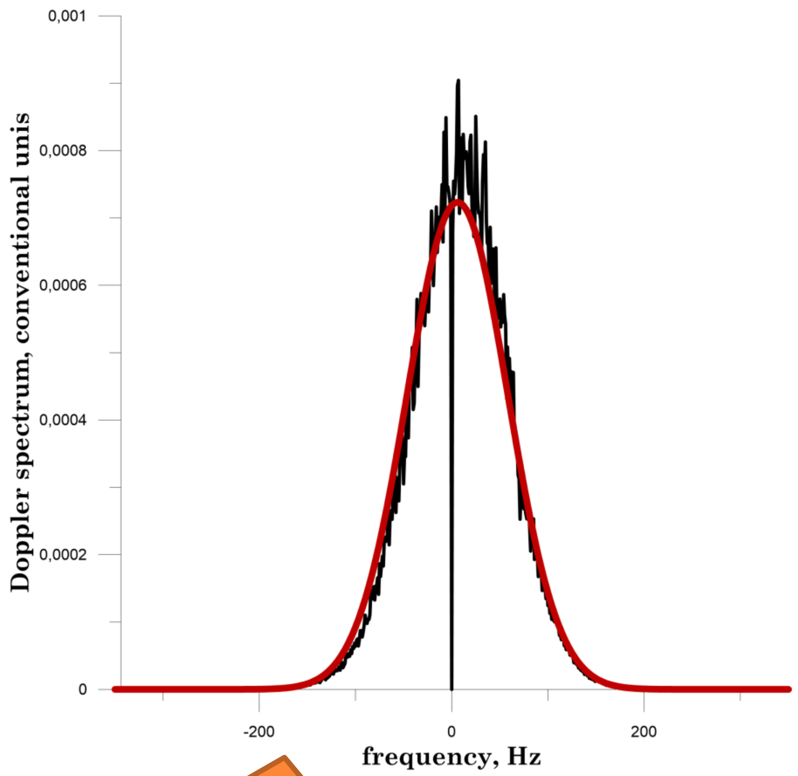
correlation coefficients

where κ and $\omega(\kappa)$ are the wavenumber and the angular frequency of sea waves connected by the dispersion relation, ϕ is the azimuth angle of wave propagation relative to the axis x, $W(\kappa,\phi)$ is the sea wave spectrum in polar coordinates, and κ_b is the boundary wavenumber

W(κ, φ)=S(κ)·Φ(κ, φ), S(κ) – measured spectrum
Φ(κ, φ) – model spectrum (Ryabkova *et al., JGR, 2019*)

Doppler Spectrum



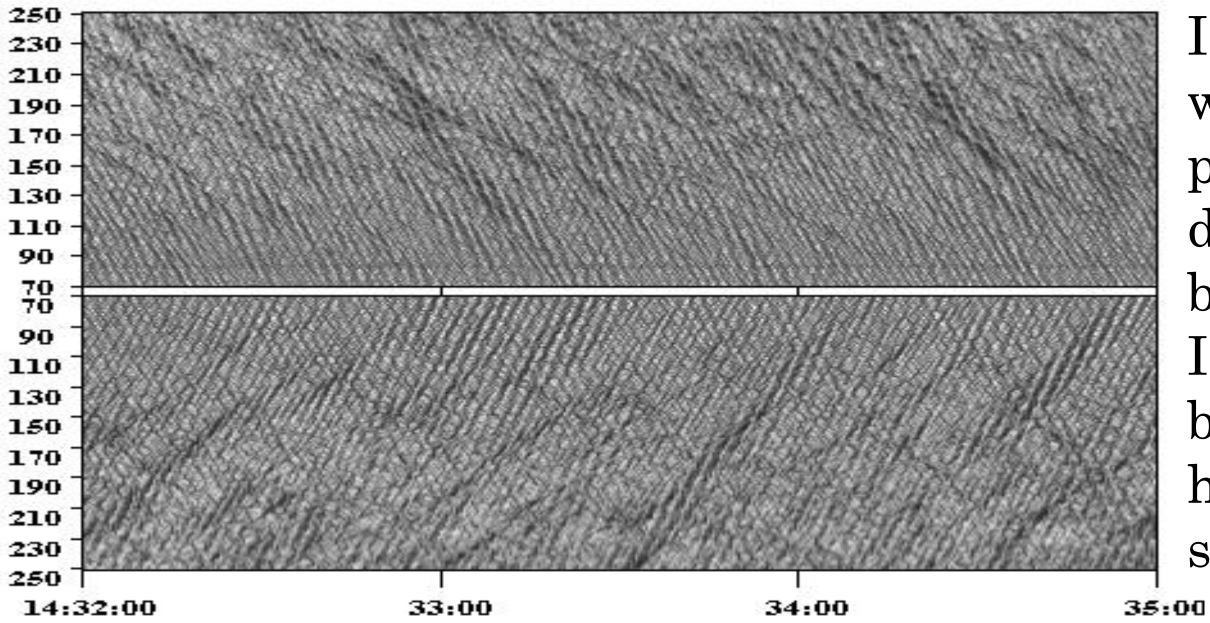


$$DS(f) = A_0 \exp\left(-\frac{(f - f_{sh})^2}{2(\Delta f)^2}\right)$$

Black curve – Doppler spectrum 13:34 – 13:44

Red curve – model Doppler spectrum

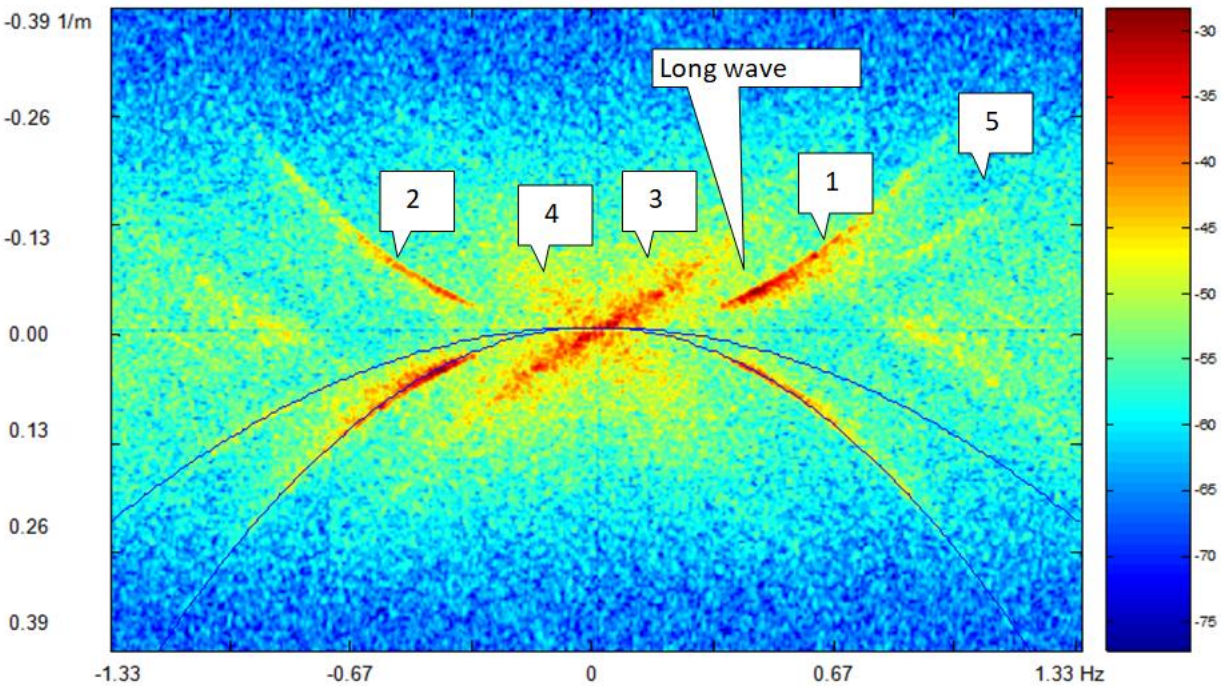
Spatial and temporal images of the sea surface from CCD



Images of long wind waves obtained from the platform for two viewing directions the angle between which was 40^0. Images are " connected" by initial parts. The height of the CCD above sea level h=15m.

In addition to long waves coming from the sea, which appear as sloping bands, the drawing shows counter waves, as well as manifestations of the group structure of waves in the form of random dark bands, the contrast of which increases to the horizon.

Spectrum of spatial and temporal images of the sea surface from CCD



The vertical axis is the spatial frequency, the horizontal axis is the temporal frequency.

1 — spectrum of long waves propagating to the shore,

2 — spectrum of “counter-propagating waves” with opposite propagation directions, and 3, 4, 5 — spectrum of the group structure of long waves. The wave spectrum is located along the parabola, defined by the equation: $k = k_d(\omega)\cos\varphi$

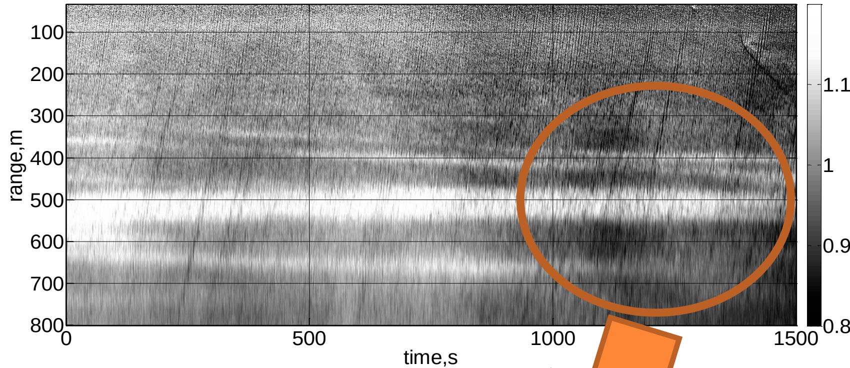
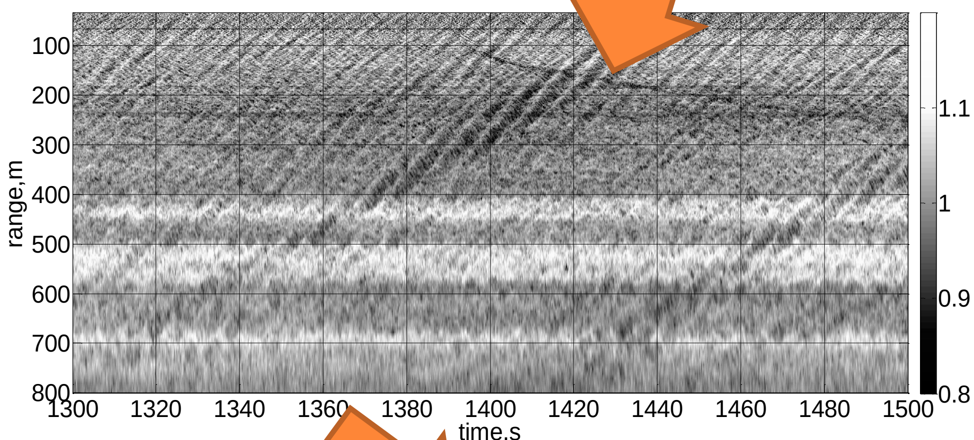
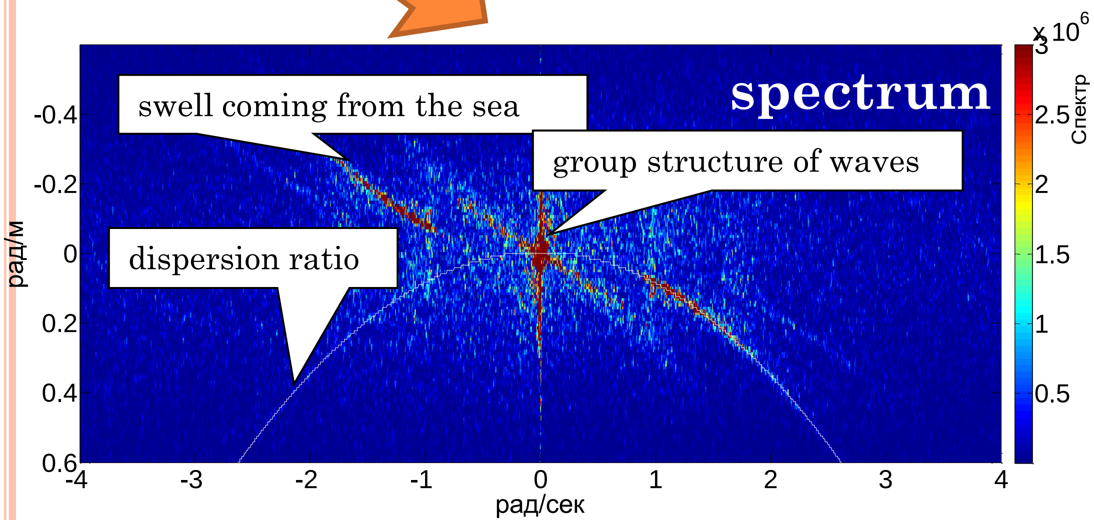
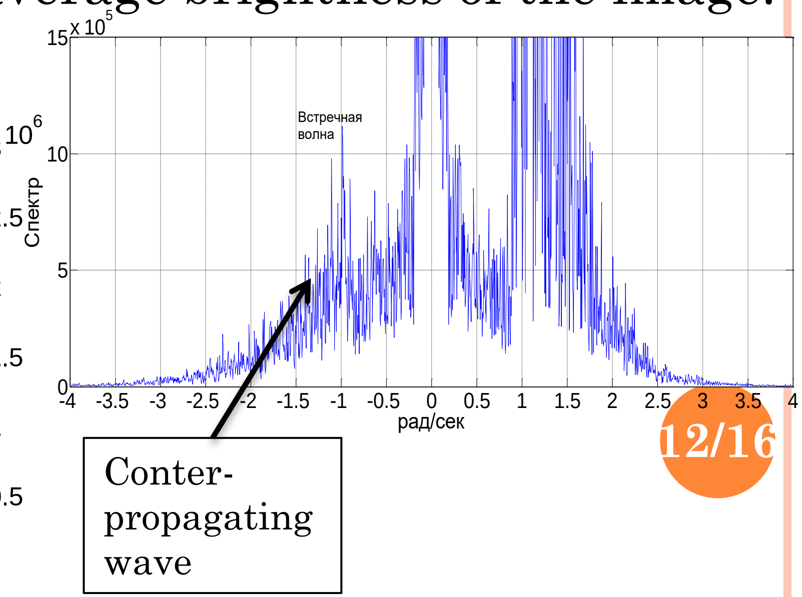


Image of the group structure of swell waves (sloping dark narrow bands). There are two systems of slicks that extend to the shore (wide slicks) and from the shore (narrow slicks).

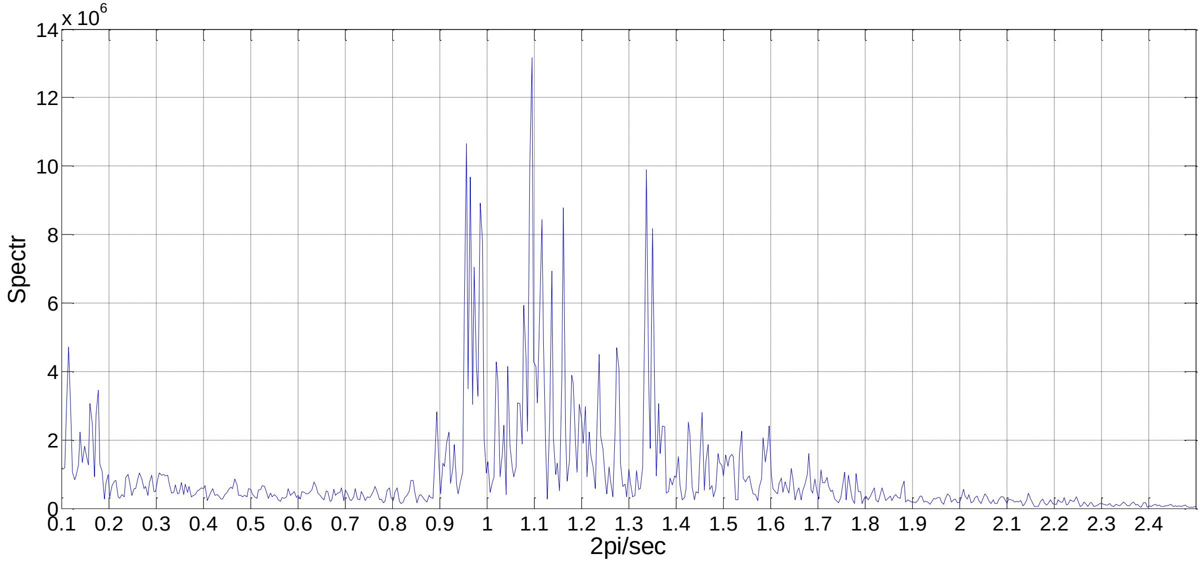


The swell wave spectrum calculated "along" the dispersion parabola. Three waves are observed (on the right) and a weak counter wave. In the middle – the response to the average brightness of the image.





Spectrum of swell



Swell spectrum. Three peaks (three waves) with frequencies:

f1 = 230 points = 1/T1 = 230/1500 Hz=1/6.52 Hz,

f2=270points=1/T2= 1/5.56 Hz,

f3=325 points =1/T3=1/4.62 Hz.

Wavelengths:

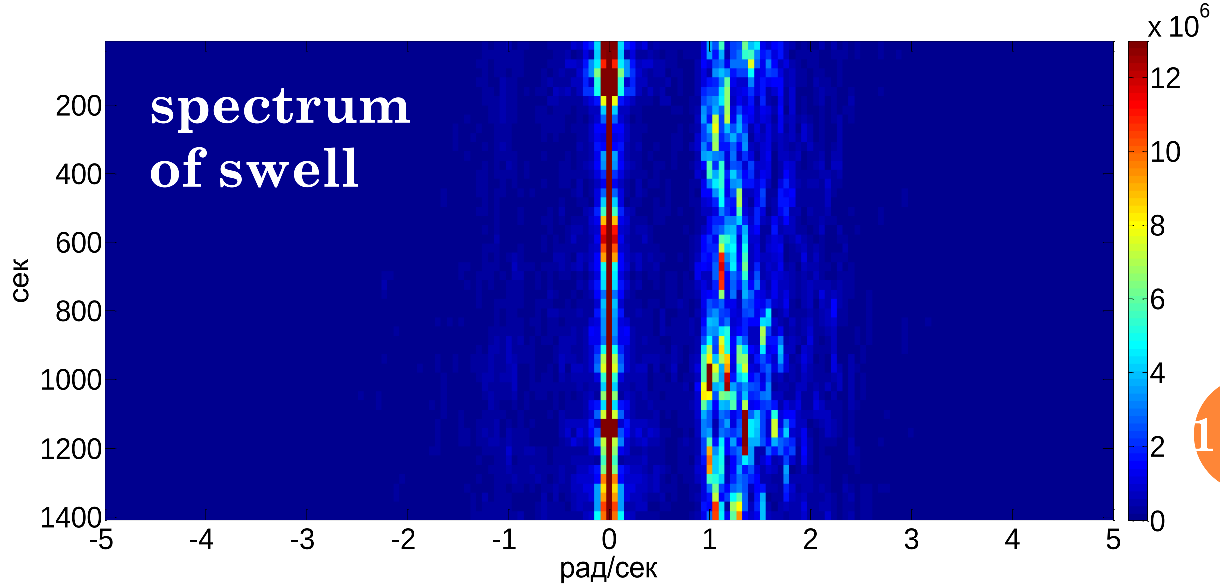
$$\lambda = gT^2 / 2\pi$$

$$= 1.54T^2$$

$\lambda_1 = 65.47$ m

$\lambda_2 = 47.6$ m

$\lambda_3 = 32.87$ m



Conclutions (Active methods)

- Acoustic wave gauge allows to measure significant wave height, wave spectrum and Doppler spectrum

- Wave spectrum measured by acoustic wave gauge is close to wave spectrum measured by string wave gauge

- Model Doppler spectrum based on the Kirchhoff approximation is correct in the case of probing at small incidence angles

CONCLUTIONS (PASSIVE METHODS)

- Long wind waves and swell waves generate "free" short waves propagating in the same direction that satisfy the dispersion equation.
- For long waves coming from the sea, there is a counter wave, the intensity of which is an order of magnitude lower than the intensity of incoming waves.
- Images the group structure of waves in the form of dark bands is well observed, and these bands are observed at a much greater distance than long waves. Images allow you to determine the group speed of long waves. Note that the same group structure is also observed for counter long waves.

Thank you for attention!

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If you are interested in the experimental data or have any questions, please, contact:

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