Development and evaluation of algorithms for retrieval of slope variance of large-scale sea waves and near surface wind speed as extension of possibilities of Precipitation Radar in remote sensing

Vladimir Karaev

Institute of Applied Physics, Russian Academy of Sciences

Advanced underwater Doppler acoustic wave gauge: new possibilities for verification of retrieval algorithms and study of sea waves and rain

1. Introduction

Modern spaceborne radars are used for obtaining information about wind vector over the World ocean. Information is assimilating in meteorological and wave climate models and significantly improves the quality of forecasts.

The problem is the fact, that radar can not measure a wind speed directly. Radar measures the backscattering radar cross section (RCS) of sea surface and it is the input parameter of wind speed retrieval algorithms.

For verification and validation of retrieval algorithms the information from sea buoys is used.

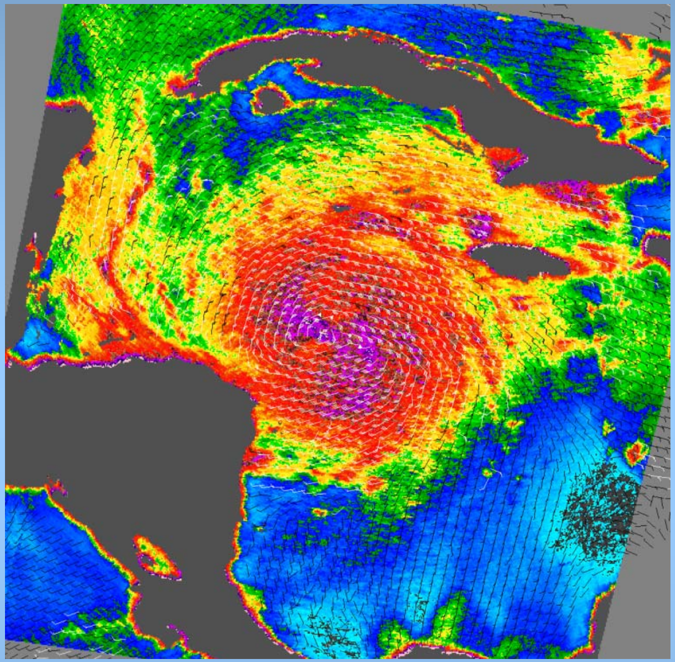
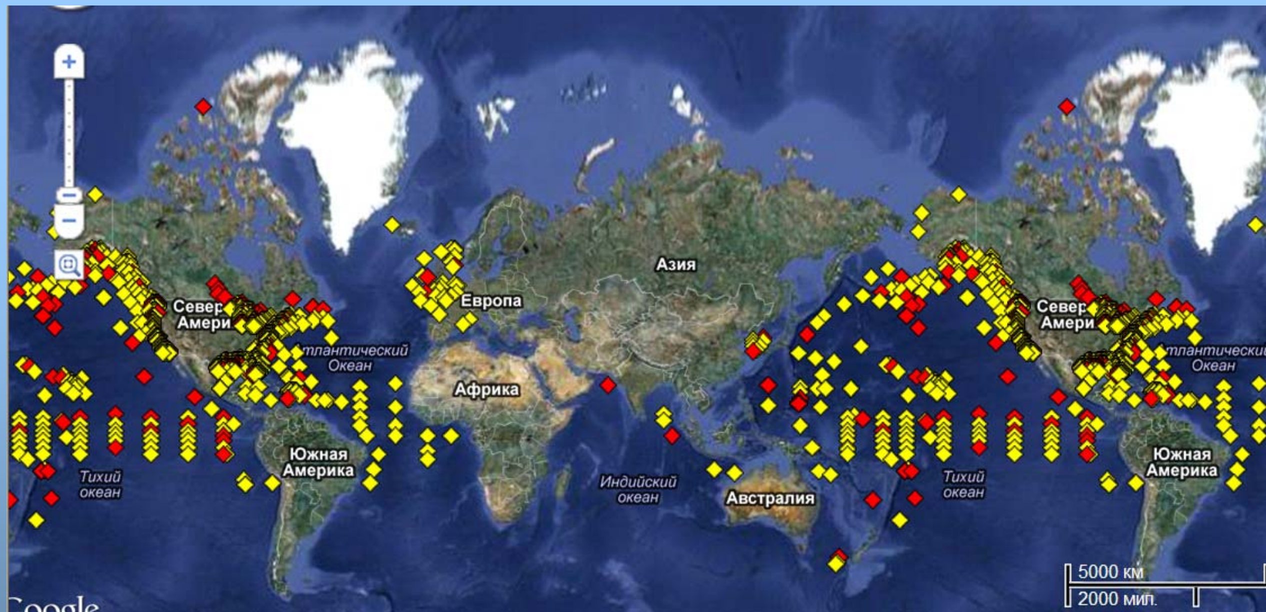


fig. 1. Wind field retrieved from scatterometer data

1. Introduction

Sea buoys are widely used in remote sensing for validation of retrieval algorithms. Sea buoy measures wind vector and directional spectrum of sea waves. The main problem of sea buoy deals with cutoff of measurable wave spectrum.



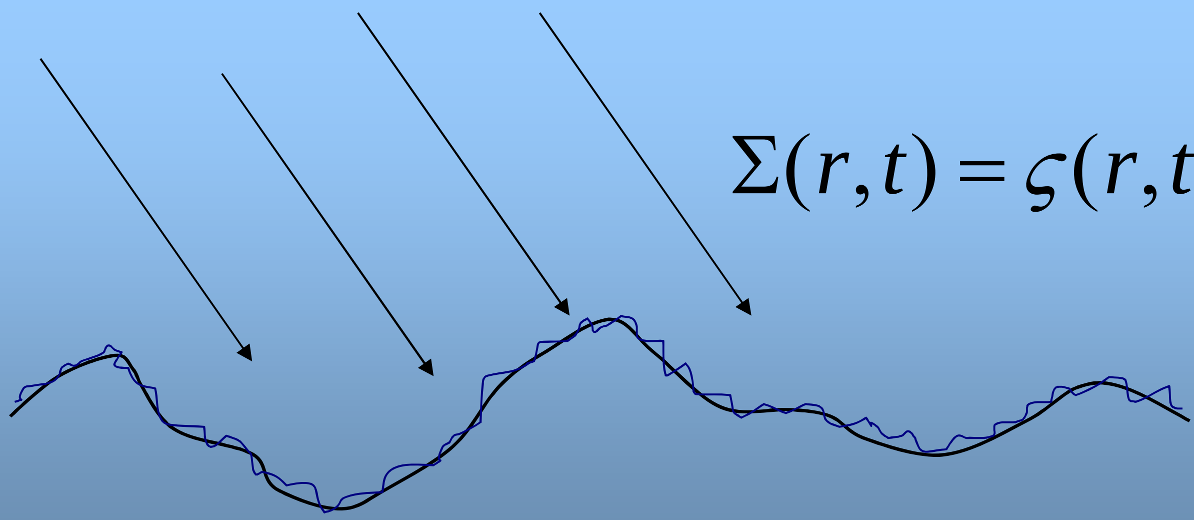
1. Introduction

The problem is the fact that analytical model describing the scattering of microwave signal from sea waves does not exist.

Well-known approach to solve this problem is a using of two-scale model of sea surface. In according with two-scale model the sea wave profile consists from large-scale waves covered by small-scale waves.

Mean square slopes (mss) of large-scale waves influences on the backscattering of electromagnetic waves at small incidence angles. Therefore mss can be measured by PR.

$$\Sigma(r,t) = \varsigma(r,t) + \xi(r,t)$$



1. Introduction

Sea buoy has a large size therefore short sea waves can not be measured.

It is not a problem for accurate measuring of SWH but we have a big mistake for mss of sea waves.

Wavelength of cutoff for NDBC buoy is approximately 6 m.

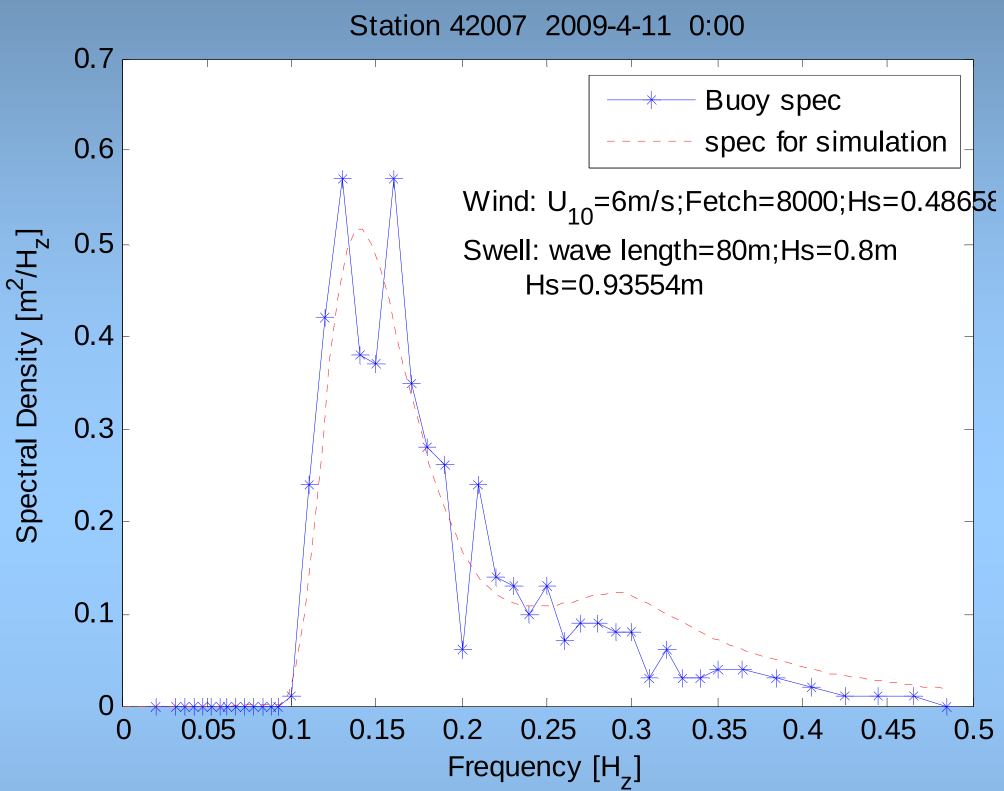


fig. 2. Spectrum of height measured by NDBC buoy

1. Introduction

Blue line – wavenumber cutoff of sea buoy.

Red line – wavenumber cutoff of two-scale model.

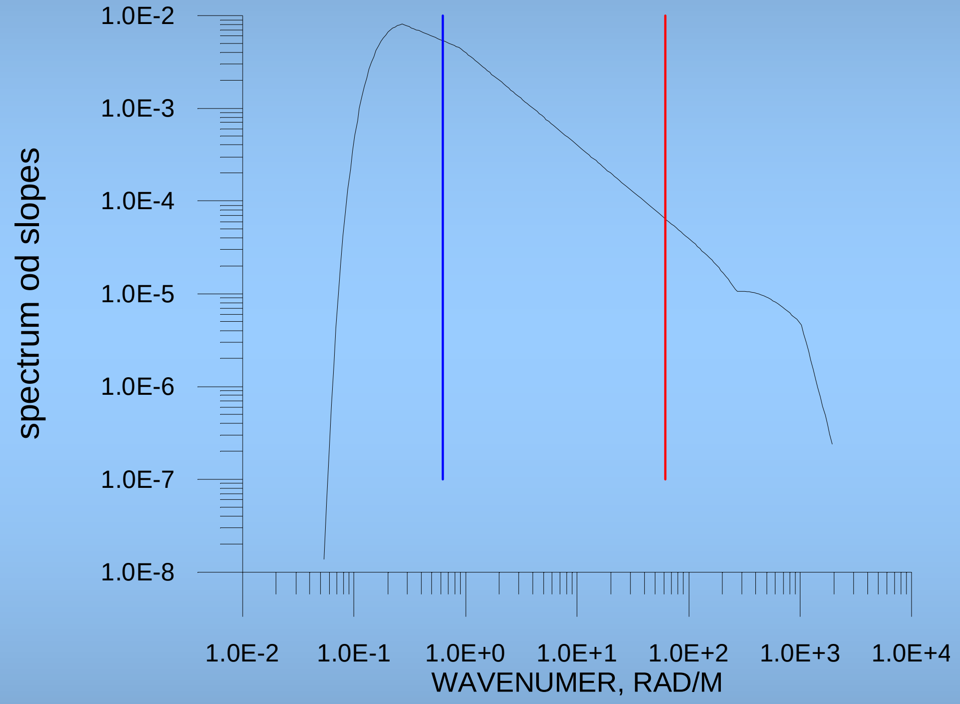


fig. 3. Spectrum of slopes (wind speed 6 m/s)

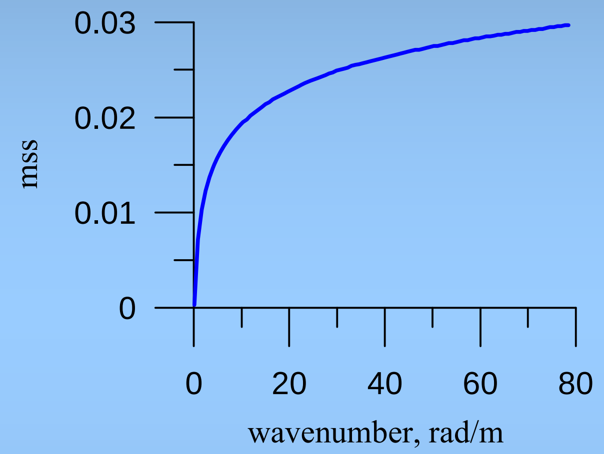


fig. 4. Dependence of mss on wavenumber cutoff

It is clearly seen that value of mss depends on the value of cutoff.

1. Introduction

EXAMPLE (wind speed = 6 m/s)

Buoy data (sea waves > 10 m)

Variance of height = 0.0435 m^2

mss = 0.0032 m^2/s^2

Two-scale model (radar wavelength = 0.03 m)

Variance of height = 0.0435 m^2

mss = 0.0214 m^2/s^2

Two-scale model (radar wavelength = 0.008 m)

mss = 0.0266 m^2/s^2

Cox and Munk's formula (optic data)

mss = 0.034 m^2/s^2

We see, that buoy's mss and radar's mss are different values. Therefore sea buoy can not be used for validation of mss retrieval algorithm.

2. Precipitation Radar

PR was developed to measure the intensity of rainfall in a broad swath around the equator (±40°).

Unlike altimeter, in PR the scanning mode is used, and the measurements of RCS are performed at different incidence angles.

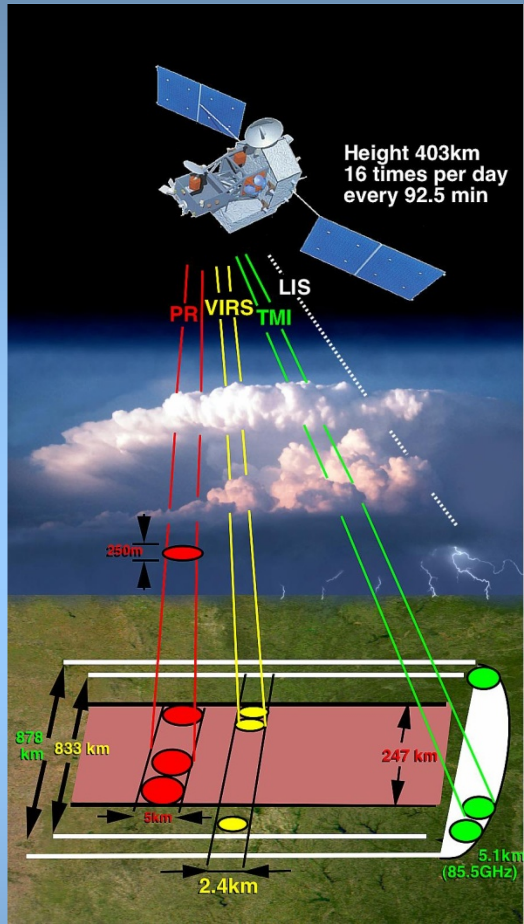


Fig.5. Probing scheme of PR.

2. Precipitation Radar

The dependence of the RCS on the incidence angle for two successive scans is shown in Fig. 6.

Increasing of incidence angle leads to decrease of RCS. Namely this effect permits to retrieve the mss.

The observed power fluctuations of the reflected signal are the main reason of errors at the retrieval of the wind speed and mss using the reflected radar signal.

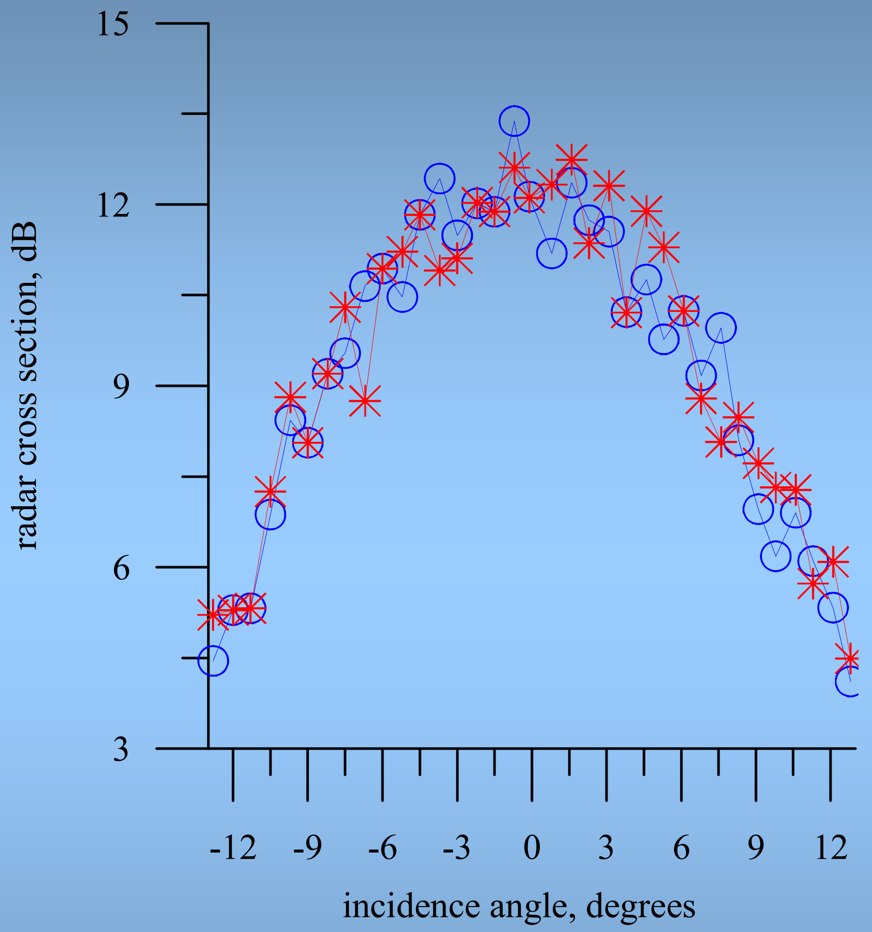


Fig.6. Dependence of the backscattered radar cross section on incidence angle for two successive scans (* and o).

2. Precipitation Radar

MSS and wind speed retrieval algorithms were developed for PR data.

We can not carry out the validation of retrieval algorithm for mss because existing sea buoys can not measure the mss of large-scale sea waves in framework of two-scale model.

Solution – we suggest to use a new underwater acoustic wave gauge for measurements of sea state parameters during sub-satellite experiments.

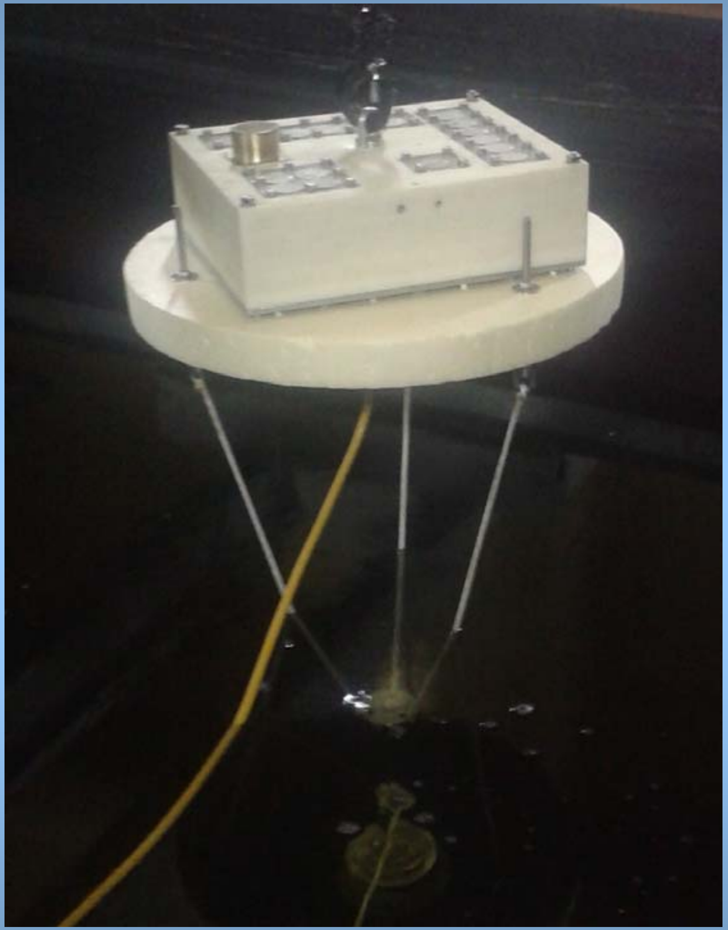
Fig.7. Underwater part of the acoustic wave gauge (wavelength 8 mm).

3. Underwater Doppler acoustic wave gauge

The working acoustic system with one transmitter and three receiving antennas was developed and the first measurements will be carried out during this summer.

New system will measure the power (RCS) and Doppler spectrum (shift and width) of the backscattered signal.

In result we have enough information to determine the all 2nd statistical moments of the sea waves.



3. Underwater Doppler acoustic wave gauge

It is known that at small incidence angles, backscattering is quasi-speqular and the reflected field is calculated using the Kirchhoff approximation. Backscattering occurs at the parts of large-scale waves oriented perpendicularly to the incident acoustical wave.

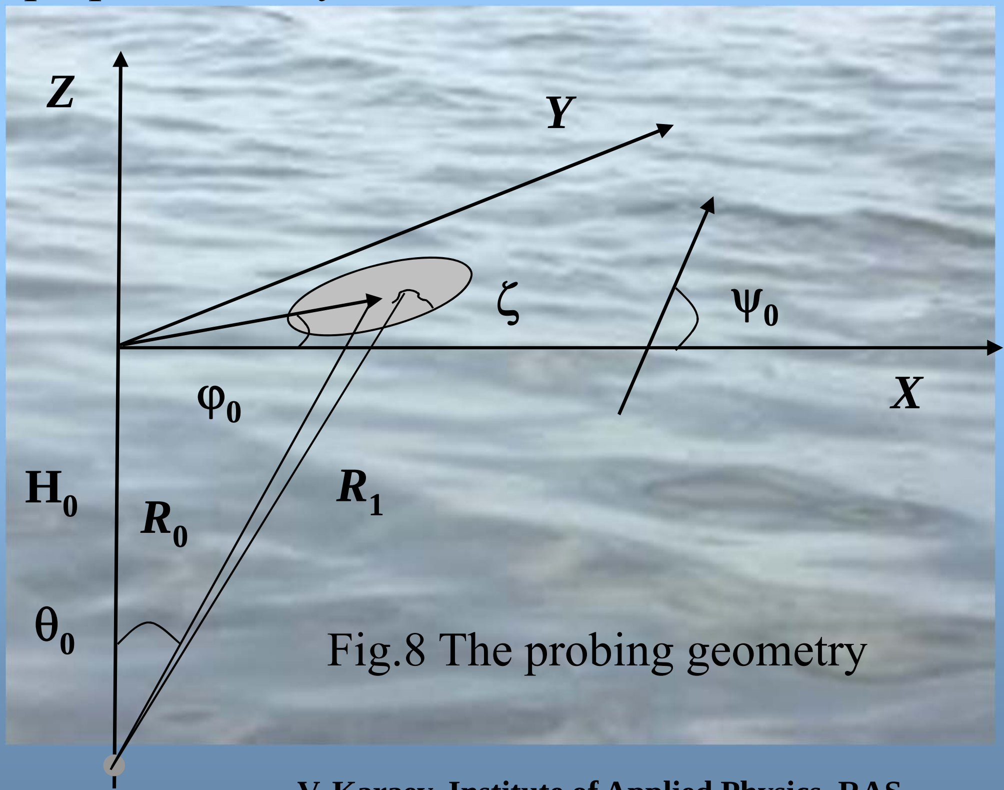


Fig.8 The probing geometry

Let us define the initial problem (see fig. 8). A sonar is located under water at the H_0 depth, the slant range to the point of reflection is R_1, R_0 is the slant range to the center of footprint and θ_0 is the incidence angle for the central point of footprint. The random function $\varsigma(\vec{r},t)$ describes the large-scale sea surface. The angle ψ_0 is the direction of wave propagation and the angle φ_0 determines the position of antenna footprint in the *XY* plane.

3. Underwater Doppler acoustic wave gauge

In the Kirchhoff approximation, the formulas for the backscattering RCS σ_0 and the Doppler spectrum width Δf_{10} are:

$$\Delta f_{10} = \frac{4\sqrt{2\ln 10}}{\lambda}\left[s_{tt}^2 - \frac{K_{xt}^2}{s_{xx}^2 + \delta_y^2/11.04} - \frac{K_{yt}^2}{s_{yy}^2 + \delta_x^2/11.04} \right]^{0,5}$$

$$\sigma_0 = 0.5\left|V_{eff}\right|^2 \Big/ \left[s_{xx}^2 + \delta_y^2/11.04 \right]^{0.5} \left[s_{yy}^2 + \delta_x^2/11.04 \right]^{0.5}$$

where V_{eff} is the effective reflection coefficient, λ is the acoustic wavelength, δ_x and δ_y are the widths of sonar beams at the level 0.5 in power in two mutually perpendicularly directions; s_{tt}^2, s_{xx}^2, s_{yy}^2 are the variances of the vertical component of the orbital velocity and the mss along the X and Y axis, respectively. The correlation coefficients K_{xt} and K_{yt} are determined by the following formulas: $K_{xt} = \langle \partial\varsigma/\partial x, \partial\varsigma/\partial t \rangle$ and $K_{yt} = \langle \partial\varsigma/\partial y, \partial\varsigma/\partial t \rangle$ where $\langle .. \rangle$ denotes the statistical averaging.

It is seen that we have 6 unknown variables in formulas, therefore 6 equations are necessary.

3. Underwater Doppler acoustic wave gauge

We suggest using two knife-like beam antennas ($\delta_x >> \delta_y$) oriented perpendicularly in the horizontal plane and one symmetrical antenna ($\delta_x = \delta_y$) at vertical probing (θ_0=0^0).

Example of scheme of measurements you can see at fig. 9.

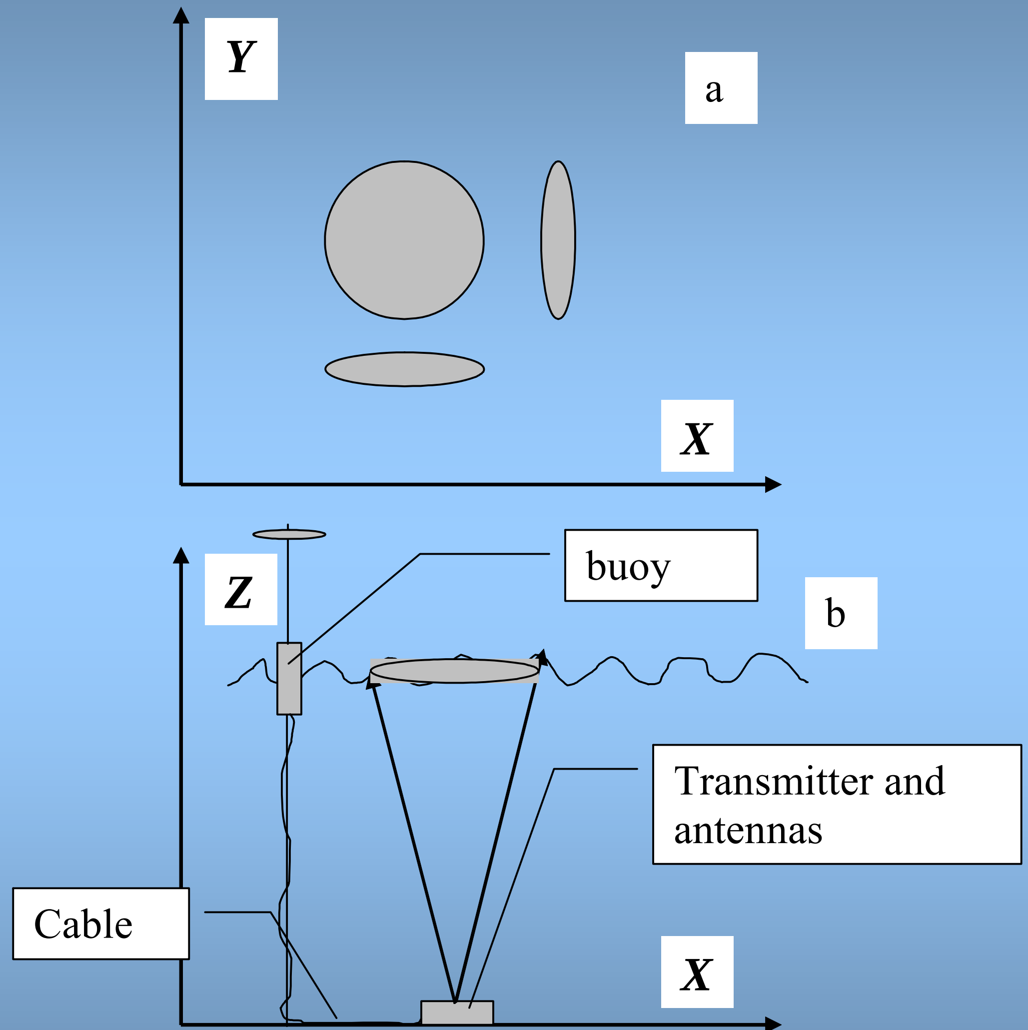


Fig. 9. Underwater Doppler acoustic system: a – scheme of antenna footprints, b - scheme of acoustic system

3. Underwater Doppler acoustic wave gauge

The advantage of the new acoustic wave gauge in comparison with conventional sea buoy is its ability to measure the characteristics of sea waves which influence at the backscattering of electromagnetic waves by sea surface.

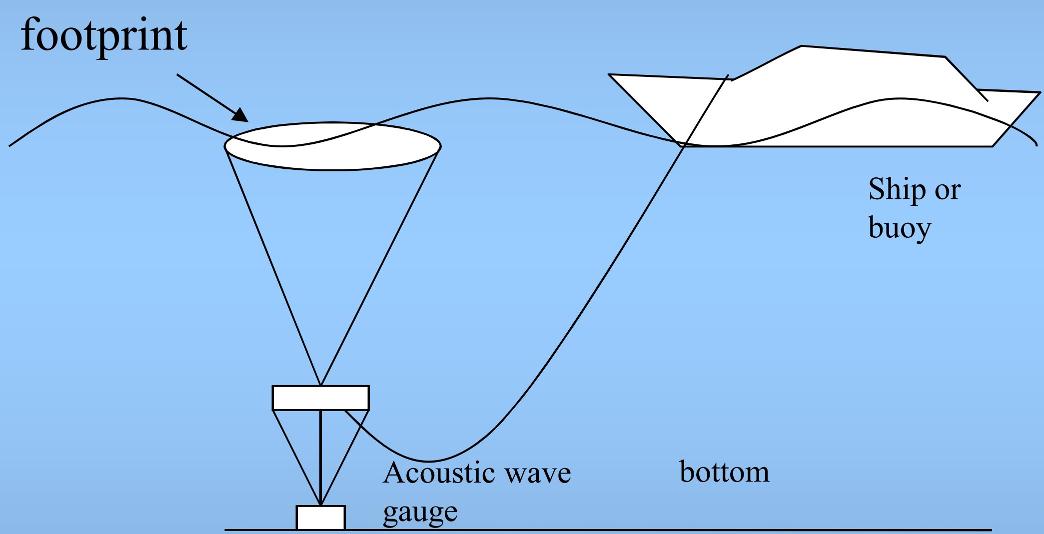


Fig. 10. Scheme of measurement

Acoustical wave gauge will be able to measure the mss, the variance of vertical component of orbital velocity of sea waves, the correlation coefficients between slopes and vertical component of orbital velocity.

4. Field experiments

Underwater acoustic wave gauge with three receiving antennas was made and the first measurements will be fulfilled at the this summer.

At the past summer we have carried out the measurements by sonar with one receiving antenna.

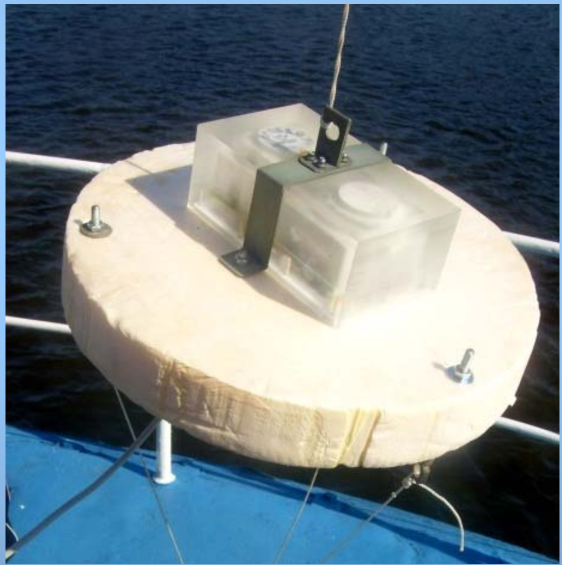


Fig. 11. Underwater Doppler acoustic wave gauge with one receiving antenna

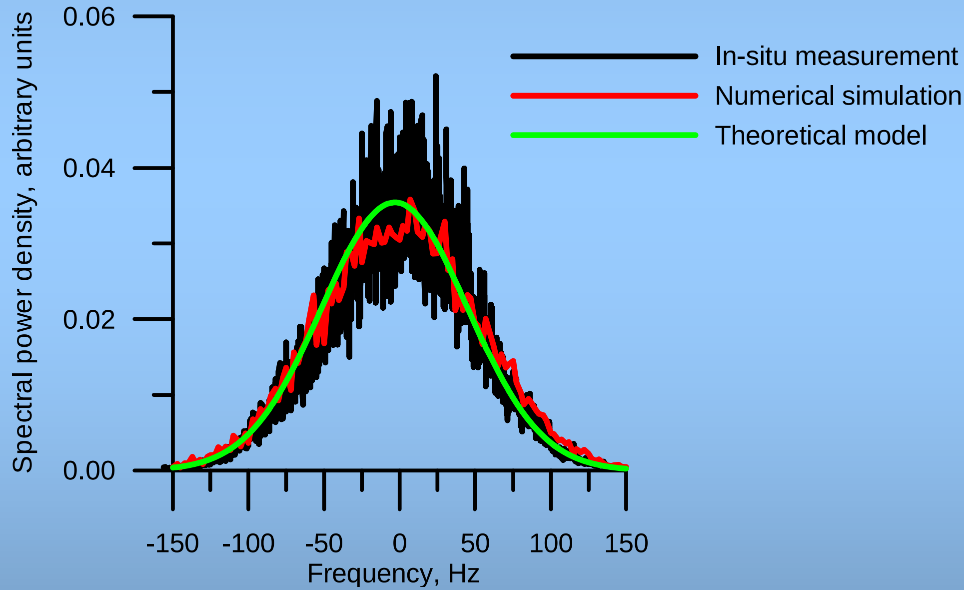


Fig. 12. Comparison of Doppler spectrums: measured, numerical simulation and theoretical model

4. Field experiments

The used acoustical wave gauge had one antenna therefore we could retrieve only one statistical parameter of sea waves, namely variance of vertical component of orbital velocity of sea waves.

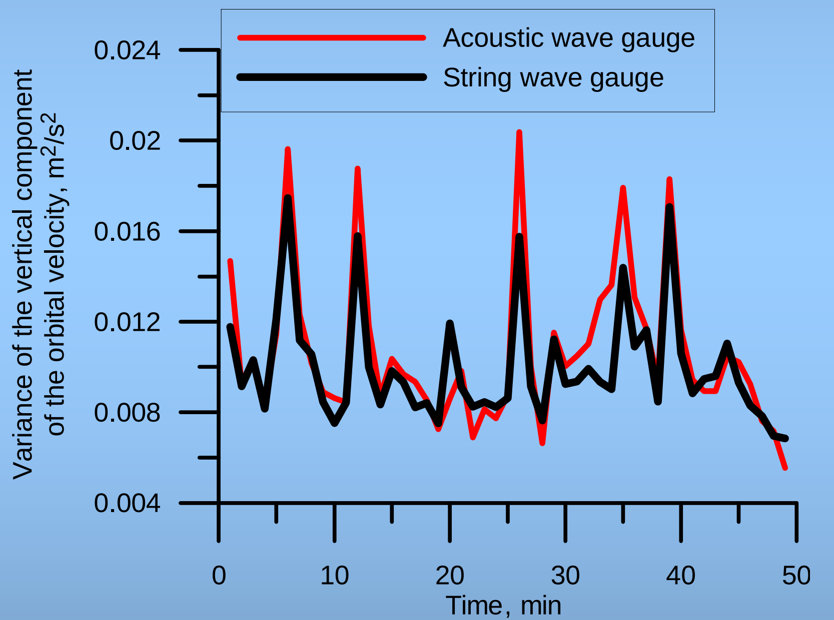


Fig. 13. Time dependence of the variance of vertical component of orbital velocity: black curve – string wave gauge, red curve – acoustic wave gauge

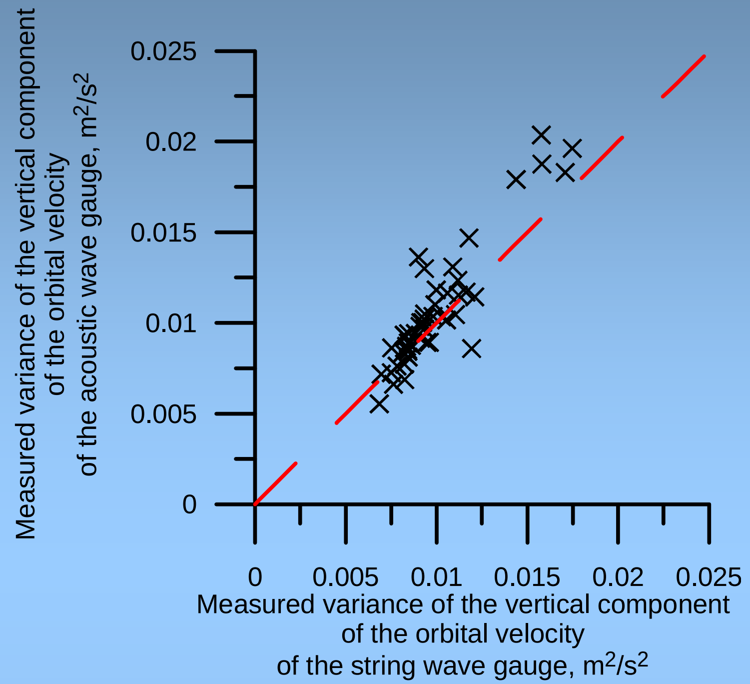


Fig. 14. Comparison of vertical component of orbital velocity measured by string and acoustic wave gauges

String wave gauge is a precision standard of gauge.

5. Laboratory experiments

Rain changes the spectrum of surface waves and this effect can be measured by radar or sonar.

The first experiments were carried out in laboratory wave tank with artificial rain.

Fig. 15. Artificial rain in laboratory wave tank

5. Laboratory experiments

During all experiments with acoustic wave gauge we used string wave gauge as source of precise data.

String wave gauge is a precision standard from the all wave gauges.

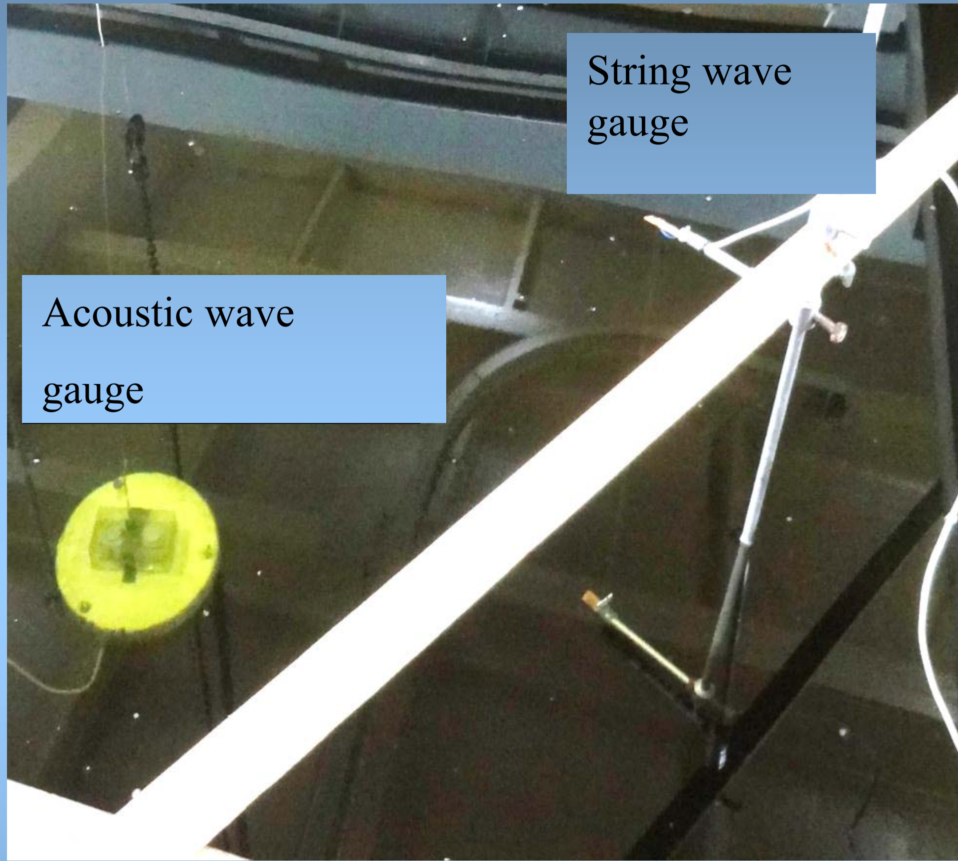


Fig. 16. Scheme of simultaneous measurement by string and acoustic wave gauges.

5. Laboratory experiments

During experiments we measure the RCS and Doppler spectrum of backscattered acoustical signal. It is seen from the figure that Doppler spectrum of the reflected signal is sensitive to rain.

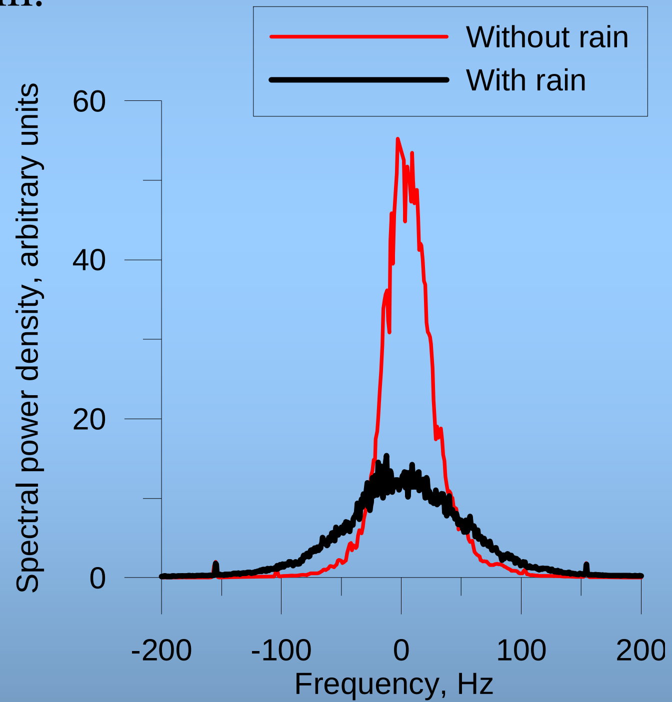


Fig. 17. Doppler spectrums: red line – waves, no rain, black curve – waves and rain.

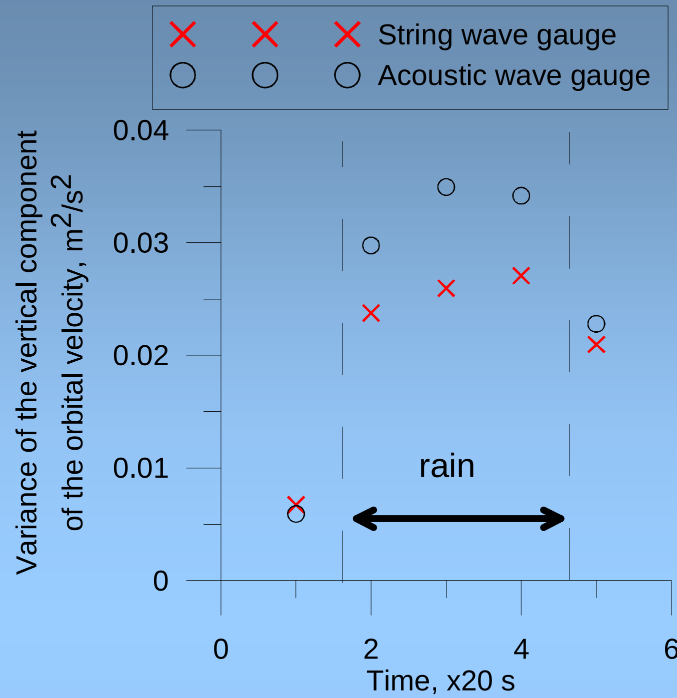


Fig. 18. Variance of vertical component of orbital velocity: circle – acoustic wave gauge, cross – string wave gauge.

Rain increases the spectral density of sea waves and it leads to the increase of the orbital velocity and mss of sea waves. In result the width of DS is wider during the rain.

6. Rain experiments

Field experiment was carried out at the Black sea. Point of measurement is shown by green cursor.

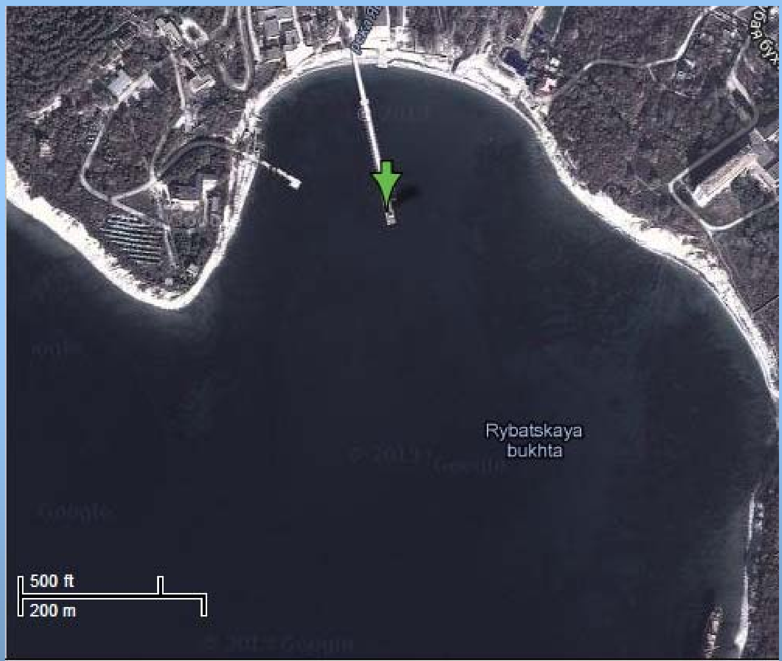


Fig. 19. Place of experiment: Black sea.

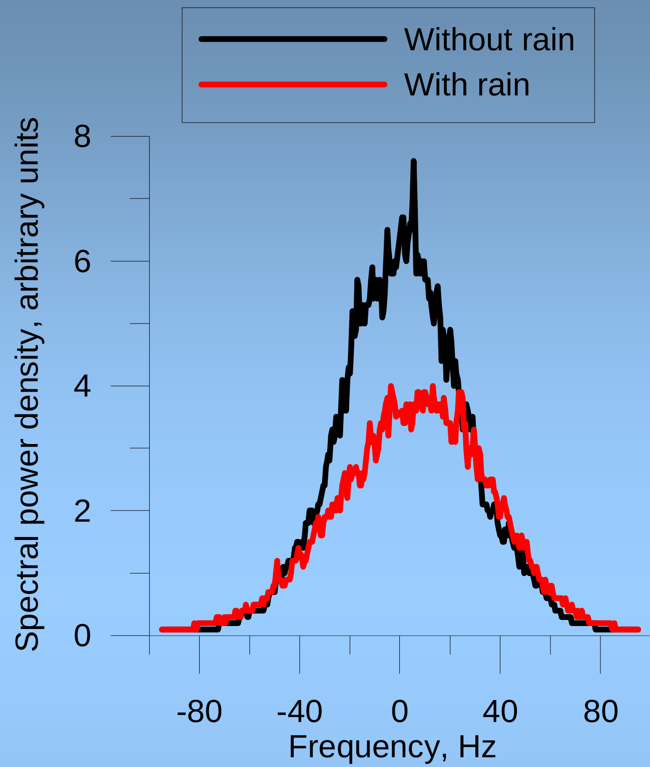


Fig. 20. Doppler spectrum: black curve – without rain, red curve – with rain.

We believe, that it is possible to estimate the intensity of rain using the change in Doppler spectrum's width.

6. Rain experiments

Wave spectrum was measured by string wave gauge. Comparison of wave spectrum measured before and during artificial rain is shown in fig. 22

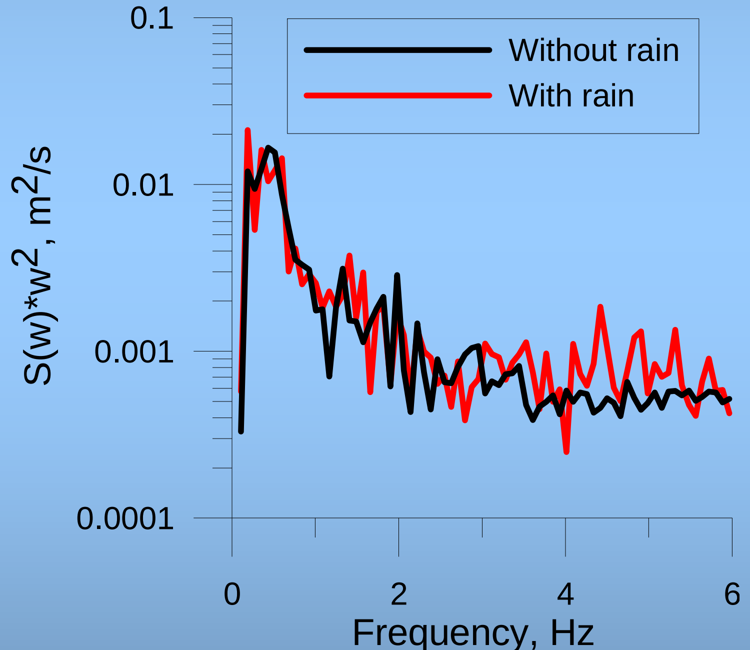


Fig. 21. Spectrum of vertical component of orbital velocity: black curve – without rain and red curve – with rain.

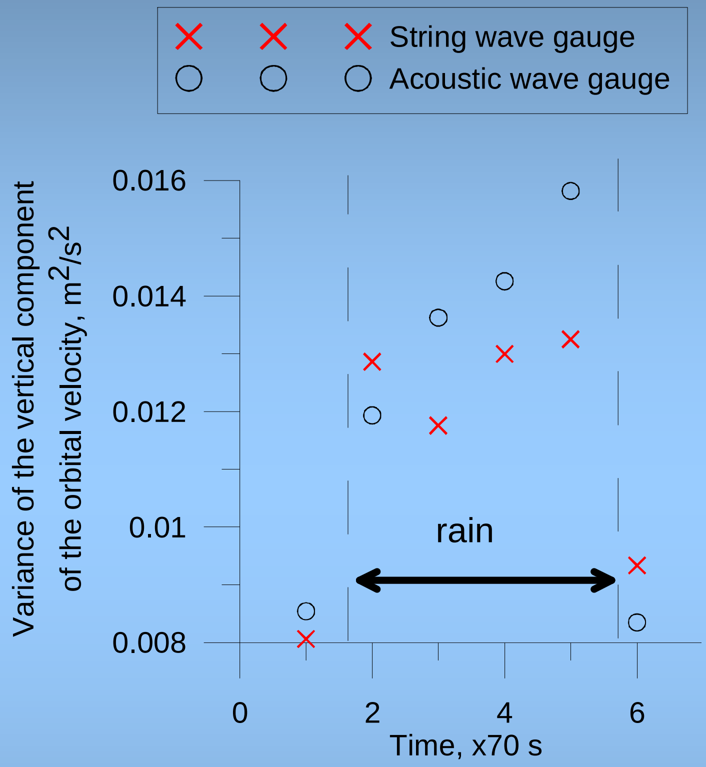


Fig. 22. Variance of vertical component of orbital velocity: circle – acoustic wave gauge, cross – string wave gauge.

7. Acoustic altimeter

The developed underwater acoustical wave gauge can measure mss and other statistical parameters of sea waves. The numerical simulation and experiments confirmed its precision.

Unfortunately, the developed acoustic wave gauge can not measure the SWH. It is very important parameter and we have continued our researches to extend the possibilities of our underwater acoustic system.

If advanced underwater acoustic wave gauge simultaneously measures the SWH and the 2nd statistical moments of sea waves, it will be a real alternative to modern sea buoy during sub-satellites experiments.

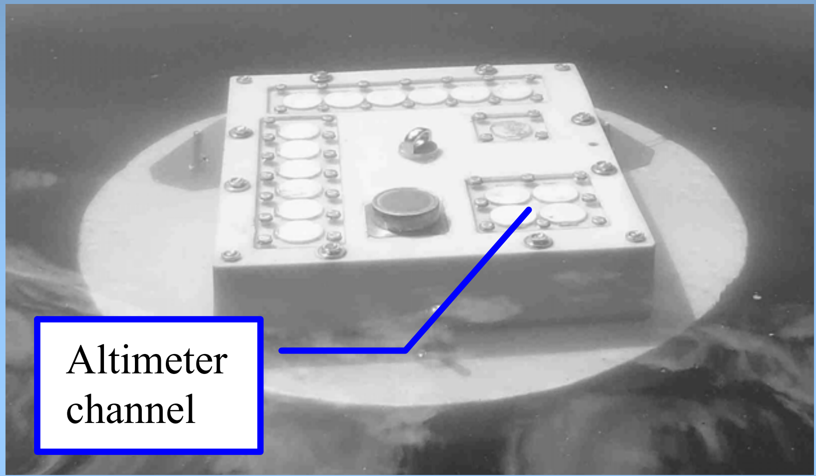


Fig. 23. Underwater acoustic wave gauge with incorporated altimeter channel

7. Acoustic altimeter

There are underwater acoustic systems (ADCP) which can measure the spectrum of orbital velocity or spectrum of height, for example, see fig. 24.

However, they have the same problem as conventional sea buoy: a large footprint and measurement of parameters only for long waves and therefore they can not measure total mss too. The cutoff frequency is approximately 0.5Hz [1].

[1] B.H.Brumleym, E.A.Terray, B.S.Strong, "System and method for measuring wave directional spectrum and wave height", U.S. Patent N 6052334, 18 April 2000

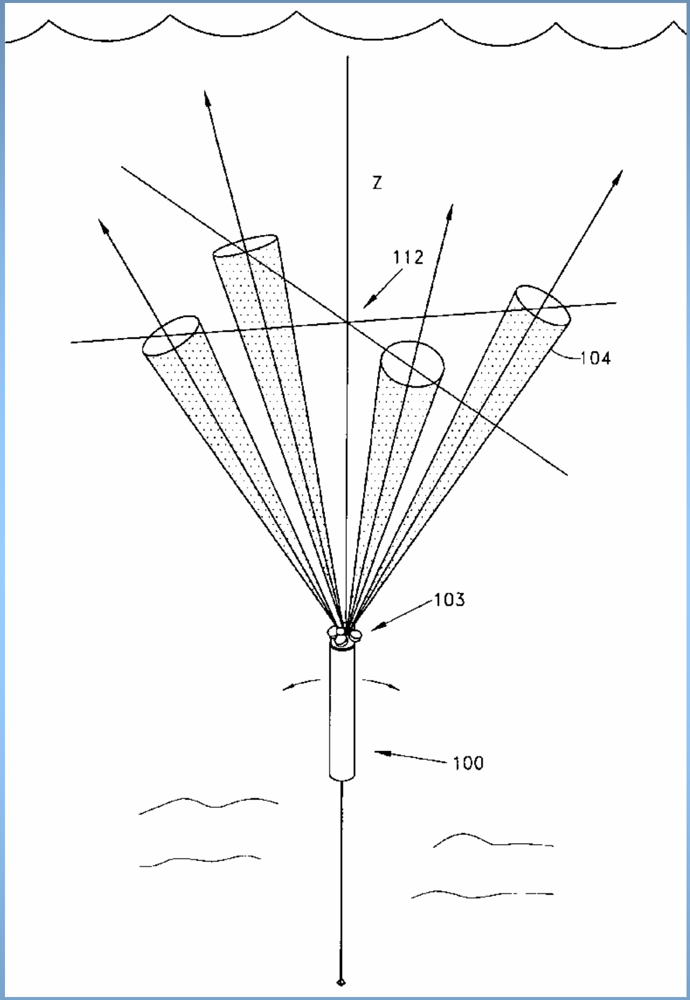


Fig. 24. Scheme of wave spectrum measurements by ADCP system [1].

7. Acoustic altimeter

At the same time, from altimetry it is well-known, that altimeter return waveform depends on SWH and altimeter is widely used for measurement of SWH and study of wave climate. Therefore we suggest to use this concept for underwater acoustic wave gauge. Slope of the leading edge of the returned waveform depends from SWH.

A few differences should be taken into account during analysis: 1) the expected depth of sonar is 50 – 300 m and size of footprint will be less or comparable with the wavelength of sea waves; 2) speed of acoustic wave is very slow in comparison with speed of electromagnetic waves; 3) it is necessary to take into account the directivity of sea waves, namely mss along X axis differ from mss along Y axis.

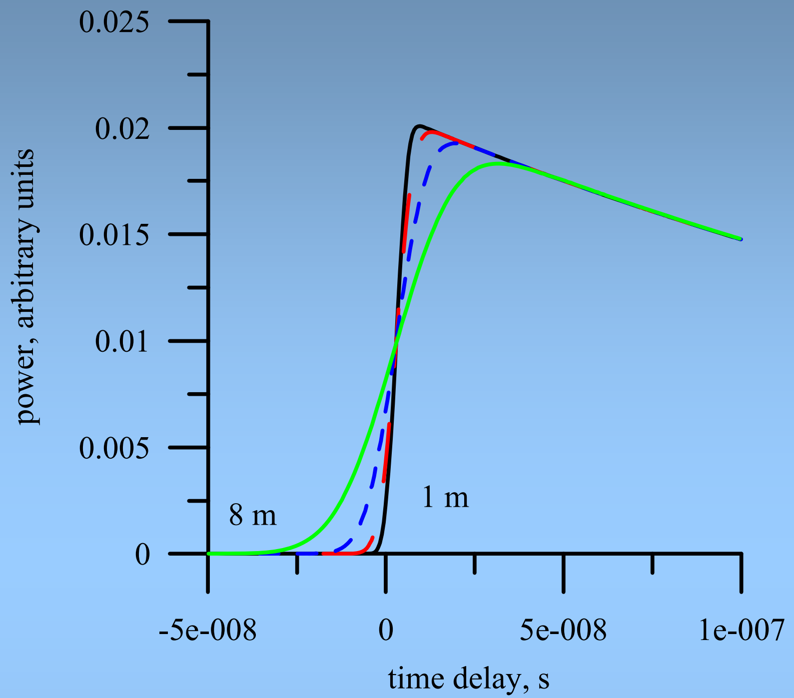


Fig. 25. Simulated altimeter returned waveforms: $\tau = 6$ ns, $H = 800$ km SWH = 1 m, 2 m, 4 m, 8 m; $\delta x = \delta y = 1°$

7. Acoustic altimeter

Theoretical model for return waveform was developed for sonar with wide antenna beam at vertical sounding. The dependences of the return waveform on SWH are shown in fig. 26.

Calculations were carried out for following values of SWH: 1 m (black), 2 m, 3 m and 4 m (green); mss_x = 0.018, mss_y = 0.012; width of antenna beam = 30°; impulse duration 50 usec, depth = 50 m.

The retrieval algorithm was developed and numerical simulation confirmed the precision of SWH retrieval for acoustical system.

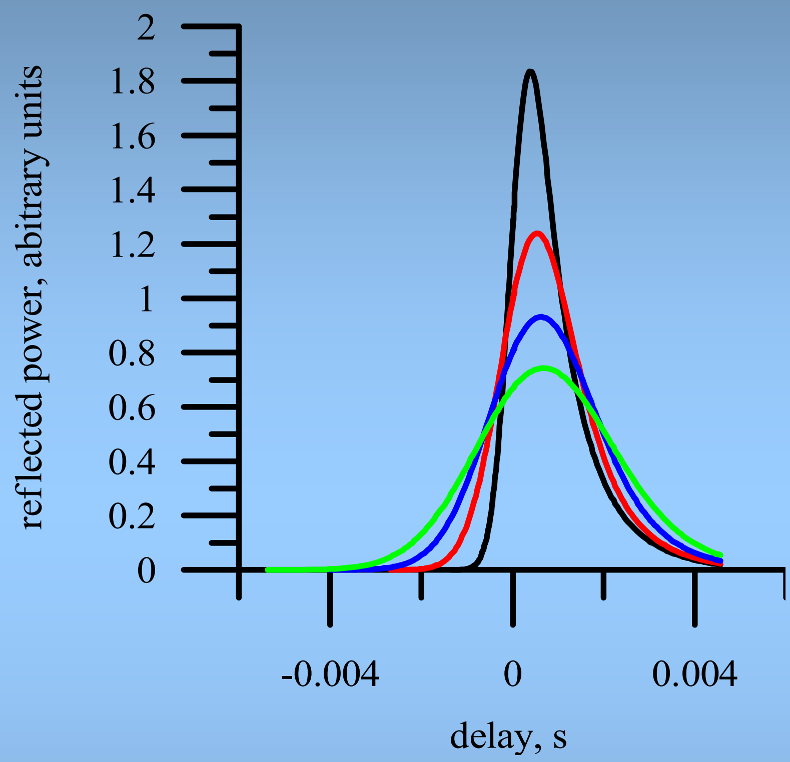
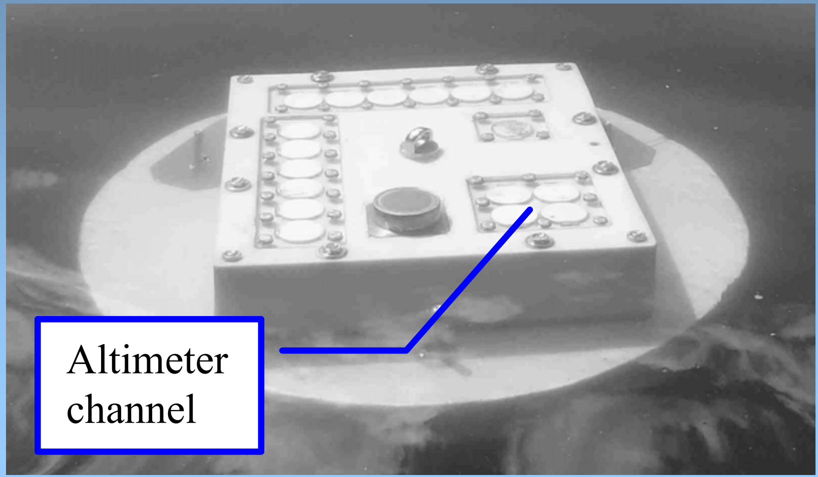


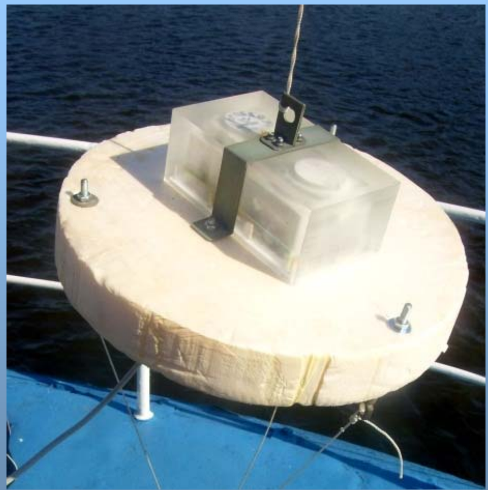
Fig. 26. Return waveform for following SWH: 1 m , 2 m, 3 m, 4 m; mss_x = 0.018 and mss_y = 0,012, width of antenna beam = 30°.

8. Conclusions

1) Theoretical model for return waveform was developed for sonar with wide antenna beam at vertical sounding. The “altimeter” channel for measurement of the return waveform was incorporated in the existing underwater acoustic wave gauge and the advanced acoustic system was obtained. SWH retrieval algorithm was developed and numerical simulation confirmed its precision. Also mean water level can be measured with high precision.
The first measurements will be done in this summer.



2) The first laboratory and field experiments with underwater acoustic wave gauge with one receiving antenna were carried out. Comparison with string wave gauge confirmed the precision of retrieval algorithms.



8. Conclusions

3) The first laboratory and field experiments during artificial rain with underwater acoustic wave gauge with one receiving antenna were carried out. Doppler spectrum is sensitive to rain.

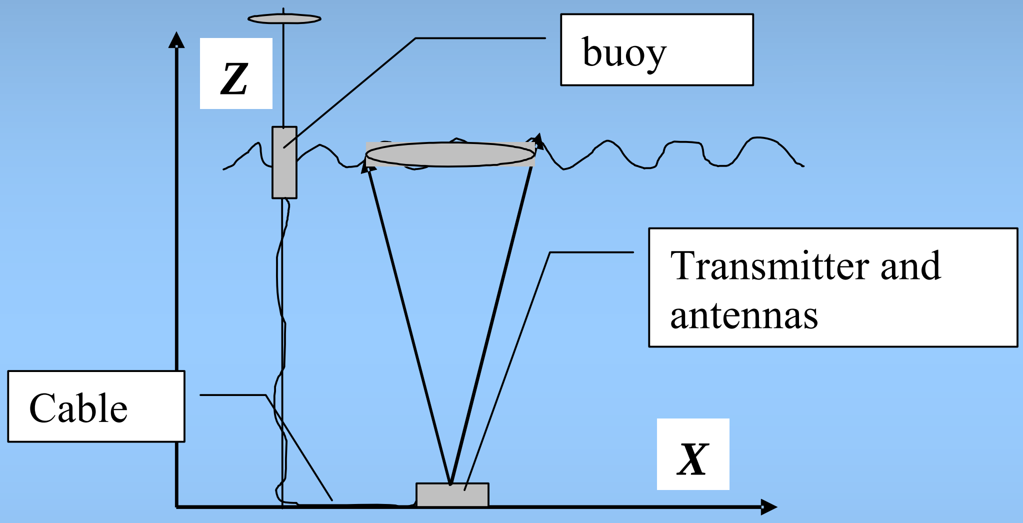
Comparison with string wave gauge confirmed the precision of retrieval algorithms.

8. Conclusions

4) The advanced underwater acoustic wave gauge with altimeter channel exceeds the existing sea buoy and other wave gauges on amount of measurable sea wave information and can control the mean sea level too.

Also acoustic wave gauge is disposed under water and can work at any wind speed and sea waves.

Advanced new underwater acoustic wave gauge will open new possibilities for validation and verification of all spaceborne radars.

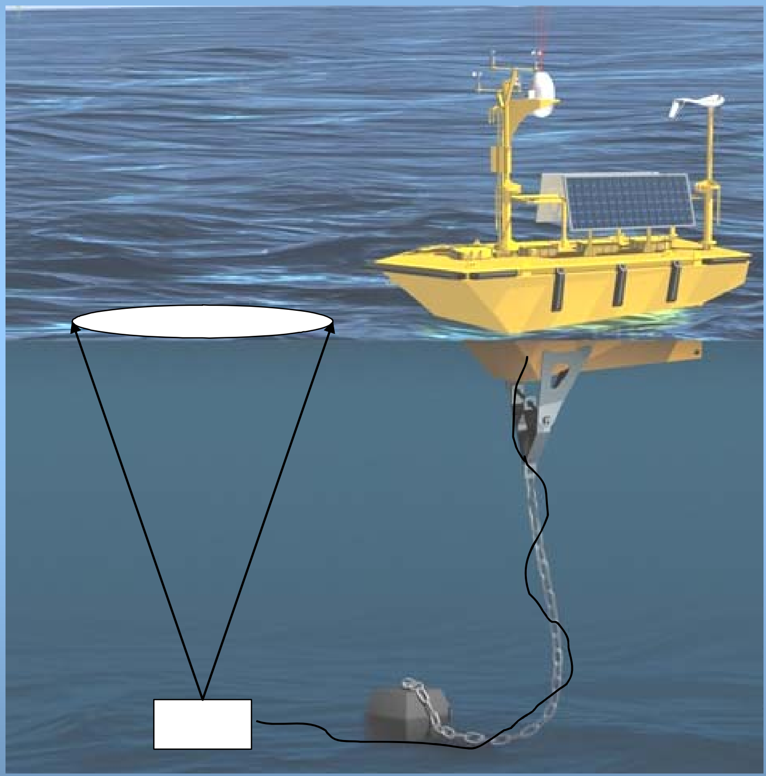


9. Ideas

a) Development of the underwater acoustic wave gauge for other wavelength – 0.021 m.

b) Development of the autonomous underwater acoustic wave gauge with float and location closely to sea buoy or combine two systems.

c) Carry out experiments for different wind speeds and sea waves (rain, no rain, different intensity of rain). Comparison with PR and sea buoys.



Thank you!

Preliminary Plan of Researches

1. formation of dataset which includes PR data and buoy data (USA and Japan buoys) for validation of data processing algorithms;

2. improvement of algorithm for the retrieval of the variance of large-scale sea surface slopes from PR data in each pixel of the swath (the image of the slope field);

3. algorithm of the wind speed retrieval in each pixel of the swath PR (the image of the wind field).

4. retrieval of the backscattered radar cross section (RCS) at normal incidence in each pixel of the swath (radar imaging of the surface);

5. experiment on the effect of rain on the backscatter Ka band using underwater acoustic wave gauge. Analysis of the influence of the rain intensity on backscattered signal from sea surface in Ka band;

6. preparation of algorithms for data processing of the new dual-frequency PR, testing and validation retrieval algorithm using buoy data. Comparison with single-frequency PR.