Determining the Parameters of Sea Wave Using the Automated Land and Underwater-Based Complexes

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Abstract. Development of combined data collection system of the sea wave parameters using automated ground and underwater-based complexes is presented. An algorithm for determining the wave height using contact and non-contact methods was developed and presented. Contact methods of data collection of the wave height are used to verify the results obtained from the non-contact method (for example, radar station). A complex testing method of the combined data collection system also was developed and presented. Experimental studies of a combined system for collecting data on the state of the sea surface on the territory of Sakhalin Island have been carried out.

1. Introduction
To predict the possibilities of developing the resources of the Russian shelf, the organization of examination and obtaining quantitative information about the characteristics of the coastal zone is extremely important. Areas of scientific and engineering research in the coastal zone are the study of waves, currents, sediment transport; study of ecosystems of coastal areas and assessment of biodiversity of organisms; inspection and monitoring of environmental conditions and anthropogenic load on the environment; bathymetric studies.

In order to get better and more complete information about the nature of the processes occurring in the coastal zone, it is very important to establish the automatic information-measuring system for carrying out systematic long-term observations. The system should use as much automated measurement techniques as possible, as well as transmit the information received in real time for its operational use in models and forecasts [1].

Existing numerical modeling methods [2,3] allow to study natural processes of different scales occurring in the seas and oceans. However, as was noted in [4], significant differences appear only on a regional scale, and are associated with features of measurement techniques. In particular, coastal zone empirical relations for wave periods in altimetry data are not universal and require additional configuration to specific regional conditions.

In this view, there is a need to conduct additional studies of the coastal zone and the formation of a database on the state of the sea surface and meteorological data. It notes the current lack of information database parameters of sea waves under different weather conditions in the regional or local waters, because of the large costs on pilot studies and the lack of a common approach in order to solve this problem.
To solve these problems, contactless and contact methods of determining the parameters of sea wave [5-9] is currently in use. However, each method alone does not give a complete picture of understanding the dangers of the sea swell.

Further considered the existing methods of contactless collection of sea wave data. Table 1 demonstrates the tools for these methods.

**Table 1.** Contactless methods for collecting data on the rough seas.

| Equipment          | Measurement                                      | Disadvantages                                                                                       |
|--------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Ground sensing     |                                                  |                                                                                                      |
| Ground sensing     | Radar station                                    | The height of waves, speed and direction of currents, near-surface wind                               |
| Ground sensing     | Radars system                                    | Water and coast pollution, wave breaking                                                              |
| Aviation sounding  | Radar                                            | The speed and direction of surface currents, near surface wind speed                                  |
| Satellite sounding | Altimeter                                        | The height of the ocean surface, a driving wind, wave heights                                       |
| Satellite sounding | Synthetic aperture radar                        | Oil slicks, a driving wind, the wave height                                                          |

In addition, we consider existing solutions in terms of the contact data collection method of sea waves (Table 2).

**Table 2.** The contact methods for collecting data on the sea waves.

| Equipment                | Measurement                                      | Disadvantages                                                                                       |
|--------------------------|--------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Buoy with accelerometer  | Statistical and spectral characteristics of the waves, speed and wind direction, speed, and direction of current | - Measurement region is small. - The probability of device loss                                      |
| Buoy with hydrostatic pressure sensor |                                                  |                                                                                                      |
| Buoy with current meter  |                                                  |                                                                                                      |
| Bottom pressure sensor   | The wave height, the flow velocity                | - Measurement region is small. - In stand-alone systems there is no data transmission in real time. |
| The acoustic pressure sensor | The wave height, the flow velocity                | - The probability of device loss - Measurement region is small. - In stand-alone systems there is no data transmission in real time. |
| Capacitive wavemeter     | wave height                                      | - Measurement region is small. - The fragility of sensor structure - Inability to determine the big waves (more than 1 meter) |
| Resistive wavemeter      |                                                  |                                                                                                      |
On the basis of the tables it can be examined that substantially disadvantage of the contactless method of sea wave data collection is the impossibility of continuous long-term studies in the selected area (especially coastal), and the need for equipment calibration using real data in a specific point of research.

For contact method of sea wave data collecting main disadvantage is the small area of measurements, and the complexity of processing a large amount of obtained data.

Also worth noting is that most used systems are stationary and do not have the ability to move. The use of mobile complexes that would carry research equipment and would produce long-term studies along the coastline without preparing the area for testing, will allow to increase the survey area, as well as to achieve the autonomy of the system.

Currently used automatic ground platforms [9-17], equipped with a wide range of sensors, measurement is carried out panoramic characteristics of the flooded zone, estimate emissions after storms, hurricanes and anthropogenic disasters. These systems are ideally suited for long-term deployment, as they allow continuous data acquisition, encompassing a few hundred meters from the coastline, they allow to study the coastal areas in the different temporal and spatial scales. However, necessary condition to obtain reliable parameters of sea wave is receiving the validation data using the contact data collection methods, such as wave buoys, capacitive wave gauge, bottom pressure sensors, as well as other technological devices.

In view of this, the relevance of developing a combined system for determining the parameters of sea waves, combining contactless and contact methods using automated complexes, is very important for obtaining operational data on the state of the sea surface of the coastal zone.

2. Development of a combined system of determining the parameters of sea waves

Taking into account the described above material, the algorithm for determining the average height of the waves in the investigated area was proposed. The algorithm consists of two subsystems. The general form of the algorithm is shown in Figure 1.

![Figure 1. The algorithm for determining the average height of waves in the surveyed area.](image)

The first subsystem includes a contactless method for measuring sea swell. The hardware of this method is established on the ground complex and consists of the radar, weather stations, video fixation device and positioning system.

The second subsystem uses the contact method of determining the parameters of sea waves and includes information derived from the capacitive wave recorder and positioning system installed on the underwater complex, such as the value of the wave height and coordinates.

Data from terrestrial and underwater complexes load into a database. The values of the heights of waves from the capacitive wave recorder goes in the absolute values (meters).

The data from the radar are represented as a reflected signal intensity.

Further, information from the land and underwater complexes is synchronized and a study point (with the navigation system of automated complexes) is allocated. This point corresponds to the place of installation of the underwater complex.

Then the correlation of the data is performing due to the inaccuracy of the synchronization of the received data from the radar and capacitive wave recorder. Correlation is performed using Pearson's method [18].
It should be noted that we will further consider only the maximum height data from the radar and capacitive wave recorder.

The next step is to build the calibration table of the maximums of wave height and the corresponding intensity value.

The wave amplitude values obtained by the capacitive wave recorder (in absolute values) can be correlated with the intensity of the reflected signal determined by radar with the help of the calibration table. In order to do this the graph \( I(A) \) is built and the approximation of the data is performed. According to the calibration table we can get the empirical relationship

\[
A_{\text{ref}} = kI_{\text{ref}} - k_0,
\]

where \( A_{\text{ref}} \) is wave amplitude in the test point (in meters); \( I_{\text{ref}} \) is the intensity of the reflected signal at the point of study; \( k, k_0 \) - calibration coefficients. These coefficients are selected with the help of the calibration table.

Further, to determine the wave height, we use an algorithm based on the processing of the received radar images. On the diagram obtained by radar stations the area of the size 500x500 meters is allocated, the accumulation of data is carried out (not less than 48 RLI) and the calculation for ratio of signal/noise (SNR) is performed (see, for example, [19]):

\[
\text{SNR} = \frac{\text{SIG}}{BGN},
\]

where \( \text{SIG} \) – the energy of the wave spectrum; \( BGN \) – background noise. They can be calculated in various ways, but the most commonly used expressions are [19-21].

\[
\text{SIG} = \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} E^{(2)}(i_x, i_y) \Delta k_x(i_x) \Delta k_y(i_y),
\]

\[
\text{BNG} = \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} F^{(3)}(i_x, i_y) \Delta f(i_x) \Delta k_x(i_x) \Delta k_y(i_y) - \sum_{i_x=1}^{N_{kx}} \sum_{i_y=1}^{N_{ky}} F^{(2)}(i_x, i_y) \Delta k_x(i_x) \Delta k_y(i_y).
\]

Here \( E^{(2)} \) is the 2-D wave number spectrum; \( F^{(3)} \) and \( F^{(2)} \) are 3-D and 2-D image spectrum respectively; \( \Delta f \) is frequency resolution; \( N_{kx}, N_{ky} \) are the extension wave number resolution.

Taking into account (2) - (4), the average value of the wave height is calculated by equation:

\[
H_x = k_0 + k\sqrt{\text{SNR}}.
\]

Calibration coefficients are only suitable for the radar station we have selected. We can restore the average value of the wave field in our region by used (5).

It is necessary to perform a calibration process from the beginning when using a radar station with other characteristics

3. Development of information collection methods based on contact and contactless methods

In view of the considered shortcomings and taking into account the developed algorithm for determining the wave height in the explored water area, a method for integrated studies of the coastal zone using the developed combined system for determining sea wave parameters for local and regional environmental monitoring systems was proposed. The structure of the methodology is presented in Fig. 2.
Further, we consider the basic steps of this method.

1. The first step is the choice of field of study. This will determine the possible route of automated systems during the test and determine the specific points where the system contact and contactless method of determining the parameters of sea waves will be set.

2. At the second stage, the graduation of the capacitive wave gauge is performed. The first calibration of the capacitance wave gauge was carried out in laboratory conditions of the Nizhny Novgorod State Technical University n.a. R.E. Alekseev in the research laboratory of modeling of natural and anthropogenic disasters. Further graduation is carried out at the test site.

   In the technique used, it was assumed that the capacitive wave gauge is an idealized instrument for collecting wave height data. It is also noted that another contact sensor can act as an idealized device, for example: a bottom pressure sensor.

   The process of graduation: for every dive millimeter, the value received from the sensor and the depth of the dive were recorded. Taking into account the immersion carried out, a table of capacitive wave gauge values was compiled with a step of 1 millimeter. The error of the developed capacitive wave gauge was ± 0.5 mm.

3. After all the organizational work has been carried out, a trip to the test site and the substitution of the combined system for determining the parameters of sea waves by means of a group of automated complexes is carried out.

   So the system collects data on the average wave height in the study area, as well as meteorological data. Data on the average wave height is obtained after processing according to the developed algorithm in paragraph 2. Meteorological data comes from a weather station installed on board a ground complex. Discretization of the obtained data was 5 minutes. That is, a wave height averaging occurs every 5 minutes.

   However, as noted in several papers [22–29], the largest wave heights have the greatest impact on the coastal zone. To this end, significant waves were extracted from the main body of data in the studied area. In order to do this, at the point of study for the entire period of the test, a time dependence is drawn up, indicating the wave heights in descending order. Next, 1/3 of the highest waves are taken from the structured data and the arithmetic average of the wave height is calculated.
We obtain the average significant wave height in the water area under study. Thereby, the averaged and significant values of wave heights in the studied area are obtained. It is also worth noting that a special contribution to the formation of waves in the coastal zone is made by: wind, ambient temperature, precipitation.

Taking into account the obtained data, the information database is prepared, which includes the averaged value of the wave height (average background) and significant wave height, wind speed and direction, precipitation, atmospheric pressure, ambient temperature, and relative humidity.

Also, when conducting research, the presence of the tide is indicated; this factor will allow further determining its effect on the wave height.

4. The constructed information database goes to the center of regional or local environmental monitoring of the coastal zone. The obtained data can be used in calculating the loads on the construction of hydraulic structures in the study area, or as initial data for modeling using standard models SWAP, WAVEWATCH III, JONSWAP, and also serve as a reference material for coastal shipping.

5. After collecting the required set of data (depending on the problem to be solved), the combined system moves to the next research site and the process of data collection is repeated.

4. Testing of the combined system for determining parameters of sea waves
According to the presented methodology and algorithms for collecting data on sea waves, experimental studies have been conducted. The stages of testing are presented below.

1. Calibration of capacitive wave recorder.

The calibration of the capacitance wave gauge was carried out in Nizhny Novgorod State Technical University n.a. R.E. Alekseev in the research laboratory of modeling of natural and anthropogenic disasters.

The sensor was calibrated in a special hydrodynamic wave tank, where an imitation of the sensor immersion in seawater took place. The average salinity of the water in the proposed test site (Cape Svobodny, Sea of Okhotsk, Sakhalin Island) is 13 ‰ [25-28]. For the calibration of the capacitive wave gauge, the operating conditions were recreated.

When conducting further tests, it was assumed that the conditions are preserved and the sensor is the benchmark when measuring the wave height.

2. Arrangement of the experiment.

The tests were carried out in the coastal zone of Sakhalin island in the Sea of Okhotsk. Radar station, weather station, positioning system and video recording system were installed on the ground-based robotic complex.

Next comes the assembly of underwater automated complex. Then the capacitive wave gauge on the underwater complex was installed. Trial launches of the complex and performance check of the equipment are carried out.

After assembly and installation of all systems on the underwater complex, it is submerged under water. Immersion is carried out at 1-1.5 meters, so that the capacitive wave gauge is partially submerged in water. It is also worth noting that the underwater complex is installed so that the capacitive sensor is at the level of the zero line.

The ground complex moves along the coastal zone in remote mode. Before the test, the ground robot approaches the edge of the hill (100-150 meters from the water surface).

The ground robot collects data on the intensity of the reflected signal at the point of the underwater robot, as well as meteorological data such as wind speed and direction, amount and intensity of precipitation, ambient temperature, relative humidity and atmospheric pressure. It is also worth noting that the irradiation range is 1.5-2 km, due to the fact that the obtained data go beyond the noise level and are difficult to track [24].

At the same time, the underwater complex transmits data on the wave height in the radar work zone (at one point) to the onboard computer of the ground complex.

The operator monitors the data collection process using the developed user interface.
An example of the data received from the radar in the graphical interface is shown in Fig. 5

![Graphical Interface Example](image)

**Figure 3.** An example of the received data on the intensity of the reflected signal (modified color palette).

According to the results of the experiments, the data processing was carried out according to the presented algorithms in paragraph 2.

1. The correlation of the obtained data
2. Making a calibration table for RLS.
3. Wave heights in the study area.

An example of the data obtained during the operation of the complexes is presented in Figure 6.

![Record Data Example](image)

**Figure 4.** Record of 50 minutes of land and submarine-based complexes.

4. Creation of a database of collected information.
5. Calculation of the relative error of the measuring complex.

According to the results of the conducted research and data processing, the information database of the parameter of sea waves has been created. An example of the obtained database is presented in Figure 6.

**5. Conclusion**

After the analysis of the processes of contact and contactless data collection on the sea waves, the shortcomings of the existing solutions were identified and a method for combining these processes into one by means of a group of mobile automated land-based and subsea-based complexes was proposed.

A combined system for determining parameters of sea waves has been developed, which includes data collection from a meteorological station, video recording of the water surface, contact and non-contact data collection through a group of automated ground-based and underwater systems for monitoring the coastal zone.

A method for integrated studies of the coastal zone using a combined system for monitoring the parameters of sea waves of a specific shelf zone, which allows collecting operational data using...
ground-based and underwater automated complexes, generating the obtained data into the information base and transmitting the data to the environmental monitoring center to refine the numerical models and compile recommendations for the construction of hydraulic structures in this area, as well as for coastal shipping has been developed.

The formulation and experimental realization of the task of measuring the sea waves in the coastal zone on the Sakhalin Island has been carried out by means of a group of ground-based and submarine-based mobile robotic systems.

6. References
[1] Korovin V P 2007 Oceanographic Observations in the Coastal Zone (Tutorial SPB: RSHU)
[2] SWAN Technical Documentation 2007 (SWAN Cycle III version 40.51A) (Netherlands: University of Technology, Delft) 98
[3] Hasselman S, Hasselman K, Komen G K, Janssen P, Ewing A J and Cardone V 1988 The WAM model - a third generation wave prediction model J. Phys. Oceanogr. 18 1715-1810
[4] Grigoriev V G and Badulin S I 2016 Performance characteristics of wind waves according to the Ship observations and satellite altimetry Oceanology 56(1) 1-8
[5] Zori A A 1991 Automation Contact Sensing of the Ocean (Vladivostok) 256
[6] Bio A, Bastos L, Granja H, Pinho J L S, Gonçalves J A, Henriques R, Madeira S, Magalhães A and Rodrigues D 2015 Methods for coastal monitoring and erosion risk assessment: two Portuguese case studies Journal of Integrated Coastal Zone Management 15(1) 47-63
[7] Gryazin D G 2000 Calculation and Design of Buoys for Measuring of the Sea Waves (SPB: SPbGITMO (TU)) 134
[8] Antonov V S and Sadovsky I N 2007 Study parameters of sea waves in the international capmos05 full-scale experiment: contact measurement with the use of five-string wave recorder Modern problems of remote sensing of the Earth from Space 4(1) 254-261
[9] Pelinovsky E N, Kuznetsov K I, Kurkin A A and Touboul J 2015 Bottom pressure caused by passage of a solitary wave within the strongly nonlinear Green-Naghdi model Doklady Physics 60(4) 171-174
[10] Beresnev P, Tumasov A, Tyugin D, Zeziulin D, Filatov V and Porubov D 2018 Automated driving system based on roadway and traffic conditions monitoring Proceedings of the 4th International Conference on Vehicle Technology and Intelligent Transport Systems 363-370
[11] Beresnev P, Kurkin A, Tyugin D and Zeziulin D 2017 Design of a modular amphibious vehicle for conducting research in surfzone Paper presented at the 19th International and 14th European-African Regional Conference of the ISTVS
[12] Zeziulin D, Makarov V, Porubov D and Kurkin A 2017 Development of a ground mobile robot for motion in conditions of coastal zones Paper presented at the 19th International and 14th European-African Regional Conference of the ISTVS
[13] Kurkin A, Tyugin D, Kuzin V, Zeziulin D, Pelinovsky E, Malashenko A, Beresnev P and Belyakov V 2018 Development of a group of mobile robots for conducting comprehensive research of dangerous wave characteristics in coastal zones Science of tsunami hazards 37(3) 157-174
[14] Kurkin A, Makarov V, Zeziulin D, Tyugin D, Beresnev P, Filatov V and Porubov D 2017 Research complex for surf zone analysis Proceedings of the 13th International MEDCOAST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation, MEDCOAST 2 787-794
[15] Kurkin A A, Tyugin D Yu, Kuzin V D, Chernov A G, Makarov V S, Beresnev P O, Filatov V I and Zeziulin D V 2017 Autonomous Mobile Robotic System for Environment Monitoring in a Coastal Zone Procedia Computer Science 103 459-465
[16] Belyakov V V, Beresnev P O, Zeziulin D V, Kurkin A A, Kurkina O E, Kuzin V D, Makarov V S, Pronin P P, Tyugin D Yu and Filatov V I 2017 Autonomous Mobile Robotic System for
Coastal Monitoring and Forecasting Marine Natural Disasters Proceedings of the Scientific-Practical Conference "Research and Development - 2016" 129-136

[17] Belyaev A M, Belyakov V V, Beresnev P O, Kurkin A A, Pelinovsky E N, Tyugin D Y and Filatov V I 2016 The mobile robotic system for monitoring the coastal zone Ecological systems and devices 8 3-10

[18] Rostova N S 2002 Correlations: Structure and Variability (Publishing House of the University of St. Petersburg vol 94)

[19] Alpers W and Hasselmann K 1982 Spectral Signal to Clutter and Thermal Noise Properties of Ocean Wave Imaging Synthetic Aperture Radars Int. J. Rem. Sens. 3 423-446

[20] Ivonin D V, Telegin V A, Chernyshov P V, Myslenkov S A and Kuklev S B 2016 Features of radar navigation systems, x-band monitoring of the coastal wind waves Oceanology 56(4) 647-658

[21] Nieto Borge J C and Guedes C 2000 Analysis of Directional Wave Fields Using X-Band Navigation Radar Coastal Engineering 40 375-391

[22] Kuznetsov K I, Kurkin A A, Pelinovsky E N and Kovalev P D 2014 Features of the characteristics of wind waves at the south-eastern coast of Sakhalin on measurements of bottom pressure Izvestiya RAN. Atmospheric and Oceanic Physics 50(2) 242-250

[23] Chernyshov P V, Ivonin D V, Myslenkov S A and Halikov Z A 2016 Analysis of the accuracy renewal of the individual wind heights when measured coastal microwave radar according to the stochastic modeling rough sea surface Current problems remote sensing of the earth from space 13(5) 68-78

[24] Garbatsevich V A, Ermoshkin A V, Ivanov I I, Ivonin D V, Kuklev S B, Myslenkov S A and Telegin V A 2017 Determination of agitation using hardware and software simple X-band radar Kerch Strait Abstracts of the 15 national open conference "Current problems remote sensing of space" (Moscow, IKI)

[25] Zaitsev A, Belyakov V, Beresnev P, Filatov V, Makarov V, Tyugin D, Zeziulin D, Pelinovsky E, Yalciner A, Yalciner B, Oshmarina O and Kurkin A 2017 Coastal monitoring of the Okhotsk sea using an autonomous mobile robot Science of Tsunami Hazards 36(1) 1-12

[26] Zaitsev A I, Kostenko I S, Kuznetsov K I, Leonenkov R V and Beresnev P O 2016 Measuring station observations of surface waves in the Sea of Okhotsk Sensors and Systems 10(207) 27-31

[27] Kurkin A A, Zeziulin D V, Makarov V S, Zaitsev A I, Belyaev A M, Beresnev P O, Belyakov V V, Pelinovsky E N and Tyugin D Y 2016 Coastal Research Okhotsk Sea with terrestrial mobile robot Ecological systems and devices 8 11-17

[28] Kurkin A, Makarov V, Zeziulin D, Beresnev P, Filatov V and Porubov D 2017 Study of coastal soil surfaces of Sakhalin island Proceedings of the 13th International MEDCOAST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation, MEDCOAST 2 775-785

[29] Solovev D B 2020 Using of Instruments of the State Support for Integration of Science and Business on the Example of Far Eastern Federal University Smart Technologies and Innovations in Design for Control of Technological Processes and Objects: Economy and Production. FarEastCon 2018. Smart Innovation, Systems and Technologies 138 pp 923-933. [Online]. Available: https://doi.org/10.1007/978-3-030-15577-3_85

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