
Measurement of Sea Wave Spatial Spectra from High-Resolution Optical Aerospace Imagery

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<http://dx.doi.org/10.5772/intechopen.71834>

Abstract

The chapter is devoted to the development of methods for remote measurement of spatial spectra of waves arising on marine and ocean surface. It is shown that in most natural conditions of optical image formation, a nonlinear modulation of the brightness field occurs by slopes of water surface elements. Methods for reconstructing the spectra of surface waves from optical image spectra with allowance for such modulation are proposed. The methods are based on the numerical simulation of water surface taking into account wave formation conditions and conditions of light entering the sea surface from the upper and lower hemispheres. Using the results of numerical simulation, special operators are built to retrieve wave spectra from the spectra of aerospace images. These retrieving operators are presented in the form of analytical expressions, depending on the sets of parameters, which are determined by the conditions for the formation of images. The results of experimental studies of the sea wave spectra in various water areas using satellite optical images of high spatial resolution are presented. In the experimental studies, the spatial spectral characteristics of sea waves estimated from remote sensing data were compared with the corresponding characteristics measured by contact assets under controlled conditions.

Keywords: wave spectra, surface waves, remote sensing, image processing

1. Introduction

Registration of spatial spectra of surface waves is actual in solving many fundamental and applied problems of modern oceanology [1–3]. Obtaining information about such spectra is important for studying various physical processes occurring near the ocean-atmosphere interface, detecting water pollution, and monitoring anthropogenic impacts on the marine areas [1, 4–12].

To obtain two-dimensional spectra of surface waves in large water areas, including hard-to-reach ones, the use of remote sensing methods based on the processing of various images obtained from air carriers and also space images of high spatial resolution is promising [4, 13–15].

An adequate estimation of such spectra formed by image processing obtained in the process of aerospace monitoring of marine areas of the seas and oceans requires the use of reconstructing operators that are functions that allow the spatial spectra of brightness fields recorded in optical aerospace images to be transformed into sea wave spectra [4, 16–18, 24]. These operators are built using numerical simulation methods based on the various conditions for the formation of aerospace images and the characteristics of remote sensing equipment [4, 16–21]. Initially, these methods were used to construct retrieving operators, which allow us to obtain wavelet spectra in the equilibrium interval [16–18]. At the present time, the development of modified retrieving operators, which are a superposition of the high-frequency and low-frequency components, is being developed and is suitable for use in the low-frequency region, including near the spectral maximum [17, 18].

This chapter describes a method for retrieving sea wave spectra from the spectra of aerospace optical images over a wide range of spatial frequencies, including the equilibrium interval, the spectral maximum, and the low-frequency region. To calibrate and verify the adequacy of the developed method, the contact data obtained in synchronous measurements with the help of an array of string wave recorders are used. The results of experimental studies carried out using the developed method are presented.

2. An approach to retrieve marine surface spectra

Rough sea surface is a random field of elevations (wave applications).

$$z = \zeta(x, y, t) \quad (1)$$

where $\zeta(x, y, t)$ is random function of sea surface elevations (elevation field); (x, y, z) is a rectangular Cartesian coordinate system in which the (x, y) plane coincides with the level of a calm (undisturbed) water surface; t is time.

Fixing the time instant $t = t_0$ in (1), we obtain a two-dimensional random function of spatial coordinates:

$$z = \zeta(x, y, t)|_{t=t_0} = \xi(x, y) \quad (2)$$

Aerospace images, which are recorded by remote methods, are used to study the characteristics of the sea surface elevation field at a fixed time $z = \xi(x, y)$. Two-dimensional signal fields that are represented in aerospace images are associated with the sea surface elevation field and can be used to estimate significant characteristics of this surface.

Since the sea surface elevation field (x, y) is a Gaussian quasistationary field, it is described quite adequately by the spectral density [2]:

$$\Psi(\mathbf{k}) = \mathbf{S}[\xi](\mathbf{k}) \quad (3)$$

where \mathbf{S} is the spectral density operator, which is proportional to the square of the modulus of the Fourier transform of the field $\xi(x, y)$; $\mathbf{k} = (k_x, k_y)$ is the wave vector.

Since optical images of the sea surface are formed as a result of reflection and refraction of light according to the laws of geometrical optics, for their analysis, the structure of the sea surface along with the field of elevations (x, y) is conveniently characterized by fields of slopes (or gradients) along the axes [2, 4, 17].

$$\xi_x(x, y) = \partial\xi(x, y)/\partial x, \xi_y(x, y) = \partial\xi(x, y)/\partial y \quad (4)$$

The gradient of the sea surface in an arbitrary direction ϕ , with allowance for (3), can be expressed as follows:

$$\xi_\phi(x, y) = \cos\phi\xi_x(x, y) + \sin\phi\xi_y(x, y) \quad (5)$$

Taking into account the properties of the Fourier transform, one can associate the spectrum of such a field of slopes with the spectrum of the field of elevations:

$$\Phi(\mathbf{k}) = (\cos\phi k_x + \sin\phi k_y) \Psi(\mathbf{k}) \quad (6)$$

The brightness field, recorded by the remote sensing equipment at a fixed time, can be expanded in a power series along the surface slopes and is represented in the form [1, 11, 12]:

$$L(x, y) = C_0 + C_x\xi_x(x, y) + C_y\xi_y(x, y) + N(x, y, \xi_x(x, y), \xi_y(x, y)) \quad (7)$$

where N is the nonlinear component of the signal, containing terms proportional to $(\xi_x(x, y))^2$, $(\xi_y(x, y))^2$, and so on. C_0 , C_x , and C_y are coefficients of the linear part of the expansion and $\xi_x(x, y)$ and $\xi_y(x, y)$ are fields of slopes (gradients of the elevation field) of the sea surface.

The contribution to the detected signal of the nonlinear component $N(x, y, \xi_x, \xi_y)$ is determined by a number of parameters: lighting conditions, wave state, and recording equipment characteristics [4, 17].

In order to change from the spectrum of the optical image $S(\mathbf{k})$, obtained under known conditions, to the slope spectrum of the sea surface $\Phi(\mathbf{k})$ in the direction determined by these conditions, the definition of the retrieving operator \mathbf{R} is introduced as:

$$\Phi(\mathbf{k}) = \mathbf{R}\mathbf{S}(\mathbf{k}) \quad (8)$$

As a rule, analytical estimates of the contribution of the nonlinear component of N to the spatial spectrum of the luminosity field are difficult; therefore, the numerical simulation method is used to solve the problem of constructing the recovery operator [1, 11–13].

The method of constructing the retrieving operator developed and described in this chapter is an extension of the method proposed in [1, 5, 6, 10–14]. To construct a retrieving operator corresponding to certain image acquisition conditions, direct numerical modeling of optical

images is performed under a given set of conditions [8–11], after which an approximation of the spatial frequency filter (transfer function) [11–14] is constructed, which allows obtaining a spatial spectrum of sea surface slopes from the aerospace image spectrum.

Parametrization of the spatial-frequency filter using a set of parameters that depends on the experimental conditions was proposed in [21]. The adequacy of the parametrization was experimentally verified in the equilibrium interval using contact data obtained by wave recorders and also by stereoscopic photography from the oceanographic platform [22].

However, the operator obtained in [21] does not allow for reconstructing the wave spectra in the region of low spatial frequencies and near the spectral maximum. To eliminate this shortcoming, an improvement was made to the method of constructing the retrieving operator and its approbation in various conditions [20, 19].

The modified retrieving operator \mathbf{R}_{mod} is represented as the product of two operators (transfer functions):

$$\mathbf{R}_{\text{mod}}(\mathbf{k}) = \mathbf{R}_{\text{low}}(\mathbf{k})\mathbf{R}_{\text{high}}(\mathbf{k}) \quad (9)$$

where \mathbf{R}_{high} is a recovery operator (transfer function) in the high-frequency region; \mathbf{R}_{low} is a recovery operator (transfer function) in the low-frequency range.

An approximation of the retrieving operator in the form

$$\mathbf{R}(\mathbf{k}) = a_0 (\exp(a_4 k^{a_5})) (\cos(\varphi - \varphi_c))^{a_3} k^{a_1 + a_2 \cos(\varphi - \varphi_c)} \quad (10)$$

where the parameter vector $\mathbf{a} = (a_0, a_1, a_2, a_3, a_4, a_5)$ is formed on the basis of experimental data obtained in complex experiments, including remote and in situ measurements of wave spectra.

3. Calibration and verification of the adequacy of remote methods

When verifying the adequacy of remote methods of measuring wave spectra, sea truth data obtained in specially conducted experiments under controlled conditions using reference techniques and means ensuring the measurement of the sea surface spectra with sufficient accuracy should be used. As such methods and means in this chapter, measurements of sea surface elevations made using a grid of string wave recorders, stereo photography from low altitudes, and measurements using wave buoys will be used.

In an experimental verification of the reliability of methods for recording wave spectra from the spectra of satellite images, we will make a quantitative comparison of the results of remote measurements with data obtained by direct measurements by contact methods.

Having obtained under the same conditions the results of remote measurements of instantaneous two-dimensional fields of slopes and elevations, as well as data of direct (contact) measurements of local time series of heights, and also using the method of comparing spatial

and temporal characteristics of sea waves based on the corresponding hydrodynamic models, it is possible to calibrate remote sensing assets for measuring sea surface characteristics.

As sources of information for comparing the results of remote and direct contact measurements of sea surface characteristics, we will use the following types of measurements:

- Measurements in which temporal sequences of elevations of the sea surface are formed using stationary contact sensors.
- Measurements using wave buoys drifting in the space survey area.
- Stereo-photogrammetric measurements performed from close distances and allowing us to directly measure the two-dimensional realizations of the sea surface elevation field with high spatial resolution.

For direct determination of characteristics of sea waves, contact methods usually employ arrays of sensors (wave recorders) measuring the parameters of sea surface (gradient, elevation, and acceleration) at one or several points spaced from each other by some distance. To estimate spatiotemporal spectra from the arrays of wave recorders, indirect iterative calculation methods are widely used, in which some hypotheses about the statistical properties of wave are postulated.

The stereo-photogrammetric processing of synchronously registered optical images of the sea surface from two different points of view (stereopairs) makes it possible to directly measure the realizations of two-dimensional fields of sea surface elevations, and calculate spatial spectra of elevations on the base of these realizations.

The stereo-photogrammetric method allows measuring the shape of rough sea surface. The drawbacks of this method include the greater complexity of processing primary data and high demands on the computing resources used.

To compare the frequency and frequency-directed wave spectra recorded by wave recorders with two-dimensional and one-dimensional spatial spectra of sea surface elevations recorded by remote data, it is necessary to develop a special approach that takes into account the features of gravitational and gravitational-capillary waves.

Taking into account the features considered, the present chapter proposes an approach to comparing satellite and contact measurements, which consists of the following:

- Conducting experiments under controlled conditions, including satellite imagery of sea surface test areas and synchronous measurements using contact equipment and/or stereo-photogrammetric imagery of the sea surface from a low altitude.
- Retrieving sea surface spectra from space images under fixed conditions for obtaining these images.
- Calculation of frequency spectra of waves from contact data obtained by wave recorders.
- Formation of wave spectra from the satellite data of stereo-photogrammetric image processing.

- Comparison of wave spectra obtained remotely with contact and/or stereo-photogrammetric measurements.

Consider the relationship between the spatial spectra of the sea surface, reconstructed from optical images, as well as frequency and frequency-directed wave spectra, measured by contact sensors, and characterize the fluctuations in sea level over time at a fixed point.

The frequency spectrum of sea surface elevations $S_{\xi}(\omega)$ characterizes the distribution of wave oscillations at a given point along the cyclic frequencies ω , $\omega = 2\pi/\tau$, where τ is the period of the wave oscillation.

The spatial wave spectrum characterizes the energy distribution at a fixed time instant with respect to wave numbers k (or spatial frequencies $\nu = 1/\Lambda$), $k = 2\pi/\Lambda$, where Λ is the length of the surface wave.

Spatial and frequency spectra of waves are functions of different arguments. They have different physical meanings and require the use of different methods of measurement. Therefore, to compare the spectra measured by different methods, a dispersion relation is used that describes the relationship between the time and spatial frequencies of waves, depending on the physical mechanisms that form the surface waves of the range in question. Within the framework of the linear hydrodynamic model, the components of the wave spectrum can be considered as elementary plane waves, for which the dispersion relation of the theory of potential waves of small amplitude that relates the cyclic frequency of the wave (ω) to the wave number k is valid. In deep water (for $kh \gg 1$, where h is the depth), the dispersion relation taking into account the contribution of gravitational and capillary forces to wave formation has the form

$$\omega(k) = \sqrt{gk + (T/\rho)k^3} \quad (11)$$

For gravitational waves (for $\Lambda > 10^{-1}$ m), the relation (11) is simplified and takes the form

$$\omega(k) = \sqrt{gk} \quad (12)$$

The dispersion relation makes it possible to establish a relationship between the spatial spectrum of $\chi(k)$ characterizing the total energy of waves with a wave number k propagating in all possible directions and a frequency spectrum $S(\omega)$ characterizing the total energy of waves with a cyclic frequency ω propagating in all possible directions

$$\chi(k) = S(\omega(k))d\omega(k) dk. \quad (13)$$

On the other hand, a one-dimensional spatial spectrum can be obtained from the two-dimensional spectrum of sea surface elevations $\Psi(k)$ by integrating over the azimuth

$$\chi(k) = \int_{-\pi/2}^{\pi/2} \Psi(k\cos\varphi, k\sin\varphi)k d\varphi \quad (14)$$

Thus, the spectrum $\chi(k)$ can be used as a base function and recalculate the spectra obtained by various measurement methods in this spectrum by means of appropriate transformations.

4. The results of experimental studies

To solve the problems of validation of the developed methods, the results obtained in three types of experiments were used [19, 22]:

- The first type of experiments consisted of carrying out space surveys and synchronous sea truth measurements of wave spectra near the stationary oceanographic platform.
- The second type of experiments consisted of carrying out a space survey of the investigated water area and simultaneous measurements of wave spectra with the help of drifting wave buoys.
- The third type of experiments consisted of carrying out studies in the short-wave region of wave spectra ($\Lambda = 0.04\text{--}1.0$ m) with the help of string wave recorders, object photography and stereo survey from the deck of the oceanographic platform.

Let us briefly summarize some experimental results of these types.

Experimental work of the first type was carried out in the area of the oceanographic platform (Katsiveli settlement, Crimea), installed at a distance of about 600 m from the shore.

For the measurement of space-time wave spectra, contact data obtained using a wave measuring unit based on an array of string wave recorders, which were a set of six resistive wave recorders measuring the elevations of the sea surface at points located in the center and at the top of the pentagon, were used.

The distance from the central string to each of the external strings was 25 cm. The main technical characteristics of this complex were as follows:

- Resolution—no worse than 3 mm
- Number of measuring channels—6
- Frequency of interrogation of channels—10, 20, 50, and 100 Hz
- The maximum height of the measured waves was up to 4 m.

During the first type of experiments, a special space imagery was conducted in the vicinity of the oceanographic platform using high-spatial resolution (0.5 m) optic-electronic equipment installed on board the GEOEYE spacecraft. A brief overview of the complex experiments conducted on September 24, 2015 at 11:52 (LT) and on September 12, 2011 at 12:06 is presented below. The presented experiments were characterized by different conditions of wave formation. During the first complex experiment, developing wind waves were observed at a near-surface wind speed of about 4 m/s. During the second complex experiment, the velocity of the near-surface wind varied from 0 to 2 m/s; however, swell waves were present in the experiment zone.

Figures 1 and **2** show the results of a joint analysis of sea wave spectra obtained from satellite and contact data under various wave formation conditions. **Figure 1** shows the results of an experiment conducted on September 24, 2015 under the conditions of developing wind waves, and **Figure 2** shows the results experiment, conducted on September 12, 2012 with weak wind

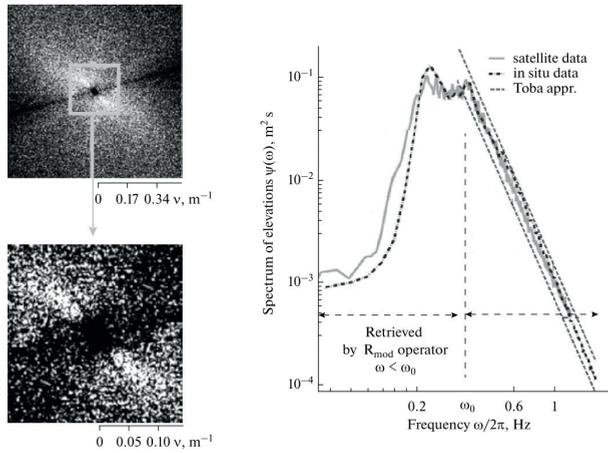


Figure 1. Comparison of the spectra of developing wind waves measured from remote and contact data of the complex experiment. September 24, 2015: (a) and (b) two-dimensional slope spectrum recovered in two intervals of spatial frequencies; (c) comparison of the one-dimensional frequency spectrum of the elevations obtained from the two-dimensional spectrum of slopes by the retrieving operator R, with the spectrum obtained from the data of the string wave recorder. The dashed lines denote the Toba approximation [23].

waves in the presence of swell waves [19, 20]. **Figures 1(a)** and **2(a)** show the reconstructed spatial spectra of sea surface slopes in a wide range of spatial frequencies, and **Figures 1(b)** and **2(b)** show the slope spectra in the region of the spectral maximum and low spatial frequencies are enlarged.

Figures 1(c) and **2(c)** show a comparison of the one-dimensional frequency spectrum of the elevations obtained from the two-dimensional spectrum of slopes with the frequency spectrum of the elevations obtained from the data of the array of string wave recorders. The conjugated spectra conditionally show the boundary ω_0 between the frequency domains corresponding to the regions of action of the high-frequency and low-frequency reconstructing operators included in the formula (9) [20].

The comparison of the graphs of one-dimensional frequency spectra of waves, shown in **Figures 1** and **2**, allows us to visually evaluate the good correspondence between the spectra measured by contact data and spectra reconstructed from remote data.

For the quantitative analysis of the correspondence between the results of remote and contact measurements, a measure of discrepancy was used, calculated from formula

$$\Delta = \sqrt{(1/N) \sum_{n=1}^N (1 - \Psi_{cn}(\omega_n)/\Psi_{contact}(\omega_n))^2} \tag{15}$$

For the complex experiment carried out on September 24, 2010, the measure of discrepancy estimated by formula (15) was $\Delta \approx 0.07$, and for the experiment conducted on September 12,

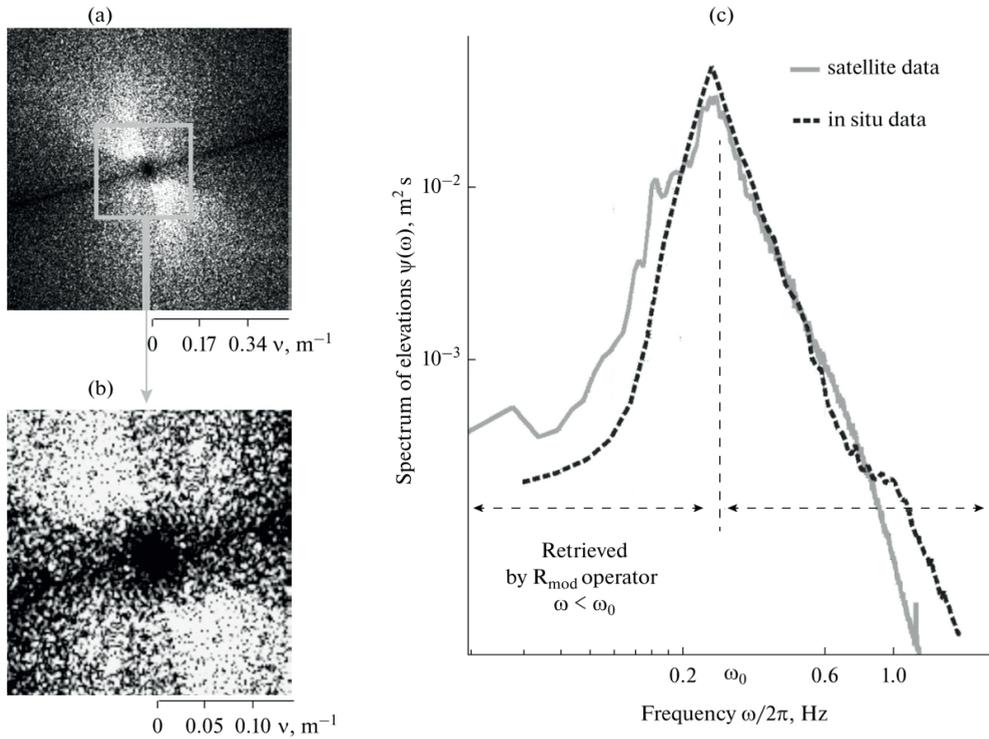


Figure 2. Comparison of the spectra of weak wind waves in the presence of swell waves measured from remote and contact experimental data. September 12, 2012: (a) and (b) two-dimensional slope spectrum recovered in two intervals of spatial frequencies; (c) comparison of the one-dimensional frequency spectrum of the elevations obtained from the two-dimensional spectrum of slopes by the retrieving operator R , with the spectrum obtained from the data of the string wave recorder.

2012, this measure of divergence amounted to $\Delta \approx 0.08$. The obtained results indicate the adequacy of the determination of wave spectra from satellite images of high spatial resolution.

During the experiments of the second type, a space survey was conducted in the vicinity of Oahu Island (Hawaii, USA) from the Ikonos and QuickBird satellites, which provided space images of high spatial resolution (0.65–1.0 m) and synchronous measurements of the frequency-angular wave spectra with the help of two wave buoys, drifting in the space survey area.

The experiments were carried out to assess the anthropogenic impacts on the water area of Mamala bay, using satellite and contact data [19]. In the course of complex experiments, space surveys and synchronous sea truth measurements were carried out, including with the help of drifting wave buoys, which ensure the registration of frequency-angle spectra of surface waves.

The following circumstance was taken into account when processing the data of the complex experiment. IKONOS and QuickBird satellites were photographed in these experiments far from the sunlight, and the resolution of the survey cameras of these satellites allowed us to fix surface waves of the submeter range (0.6–1.0 m). Under such conditions, the nonlinear components of

the brightness field of the sea surface make an insignificant contribution to the spectra of satellite images. In this connection, in the analysis of complex experiment data, it is permissible to use the linear model, according to which the two-dimensional spatial spectra of satellite images $S(k_x, k_y)$ are linearly related to the spatial spectra of sea wave inclinations $\Psi_\varphi(v_x, v_y)$.

The results of comparison of the wave spectra obtained on the basis of remote data and drifting buoy data are shown in **Figure 3**.

During the processing, fragments of satellite images with dimensions of 1024×1024 or 2048×2048 pixels were selected in such a way that the fragment overlapped the wave buoy path at

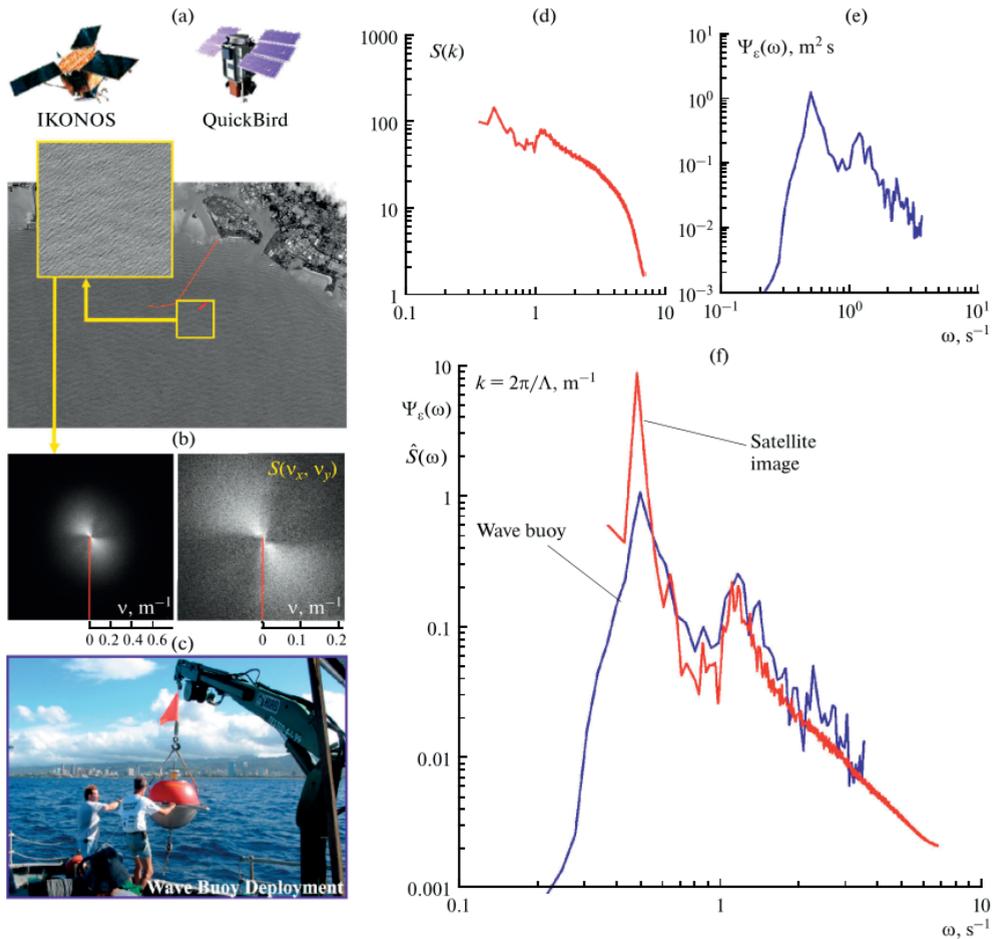


Figure 3. The results of a joint analysis of sea wave spectra obtained from space images and from drifting wave buoys: (a) the initial space image and its fragment used for processing; (b) two-dimensional spatial spectrum of the selected fragment and its enlarged central part (right); (c) installation of a wave buoy; (d) a one-dimensional spatial spectrum obtained from the two-dimensional spectrum of the satellite image; (e) the frequency spectrum obtained by a wave buoy; (f) comparison of frequency spectra obtained by different methods.

the time of shooting (see **Figure 3a**). The data obtained by measurements with a wave buoy (see **Figure 3c**) were selected in such a way that the moment of the survey was as close as possible to the end of the half-hour accumulation of data obtained by the buoy. For the selected image fragments, two-dimensional spatial spectra $S(k_x, k_y)$ were formed, examples of which are shown in **Figure 3b**, and according to measurements by wave buoys, the frequency-angle spectra of the elevations $\Psi_\varepsilon(\omega, \theta)$ are constructed.

Two-dimensional spectra of satellite images $S(k_x, k_y)$ (see **Figure 3b**) also yielded one-dimensional spatial spectra $S(\mathbf{k})$ (see **Figure 3d**), and from the frequency-angle spectra of the elevations $\Psi(\omega, \theta)$ obtained by wave buoys, the frequency spectra of $\Psi(\omega)$ (see **Figure 3e**) were constructed in the chosen directions.

From the one-dimensional spatial spectra obtained from two-dimensional spectra of satellite images using the dispersion relation for gravitational waves, the frequency spectra $S(\omega)$ were determined from the formula (12).

An important stage in the comparison of wave spectra obtained from space images and data from wave buoys is the detection of additional spectral harmonics due to anthropogenic effects on the surface waves caused by buried wastewater outfalls in the region of the experiments [7–12]. Such spectral harmonics arise under the action of high-frequency internal waves generated by turbulent jets of nonsalty water discharged into the saline marine environment through the diffusers of deep outfalls. Similar effects are caused by various physical mechanisms, analyzed in [14, 15].

The conducted experiments' results and comparison of additional spectral harmonics detected on the base of satellite image spectra and wave buoy data have confirmed the efficiency of remote methods for detection of manifestations of anthropogenic impacts on the water environment taking into account wave spectra changes.

Experimental work of the third type was performed completely on the oceanographic platform in Katsiveli settlement (Crimea).

To verify the adequacy of the methods for retrieving sea wave spectra in the 0.1–1 m short-wave range, the results of complex field experiments of the third type were analyzed. These experiments were carried out at an oceanographic platform, including conventional and stereo survey, as well as contact measurements of wave spectra using a wave recorder array. Stereo surveying of the sea surface was carried out from the working platform, which was located at a height of 16 m above sea level with a 10.2 m basis using stereocameras with a focal length of 99 mm. From the measured elevation field samples, the spectra $\Psi_\phi(k_\phi)$ were calculated using the interpolation and discrete Fourier transform procedures. Simultaneously, with the stereoscopic shooting on the platform, contact measurements of the frequency spectra of waves were performed using a wave spectrograph providing registration in the frequency range of 0.1–15 Hz with a tunable filter bandwidth of 0.1 Hz. In the wave spectrograph, a method for sequential analysis of the frequency spectrum was realized by automatically tuning the transmission frequency of a narrowband filter in a given interval [22].

Images of the sea surface obtained during stereo photography were also used to retrieve the wave spectra by a nonlinear multiposition method [22]. At the same time, fragments of two

stereopair images were analyzed on which a surface area processed by a stereo-photogrammetric method is presented. Experimental conditions: the zenith angle of the Sun was 30° (the images were recorded with a cloudless sky), and the wind speed was 5 m/s. During the experiments, the wind blew from the shore, so the acceleration of wind waves did not exceed the distance from the platform to the shore, which was ~ 600 m.

As the main characteristics for comparing the wave spectra obtained by different methods, the rms elevation σ_ξ and the power exponent p_χ in two wavelength intervals Λ were chosen: from 0.1 to 1 m and from 0.04 to 0.4 m. The wave spectra, measured by different methods, were recalculated in spatial spectra of $\chi(k)$.

In the presence of solar glitters in the image, which cause a significant nonlinearity of the transfer function, which connects the slopes and the brightness of the elements of the sea surface, systematic errors arise in retrieving the spectra of waves. Such errors were eliminated by means of nonlinear retrieval filters adapted to the wave characteristics using an iterative procedure for retrieving the wave spectra [20, 25].

Quantitative estimates of these errors were given in [17, 21], where it was shown that even with the use of images containing solar patches, two iterations of retrieving obtained from different positions are sufficient to reduce the relative error in measuring the integral spectral energy to $\approx 3\%$ and the error determines the exponent of the power-law approximation of the wave spectrum to ≈ 0.03 .

To correct the spectra of elevations obtained by the stereo method, the noise of digitization resulting from errors in measuring the elevations of the surface during stereo-photogrammetric image processing was taken into account. It was assumed that the noise is additive, so their spectrum was subtracted from the spectra measured during processing [22].

The form of short-wave spatial spectra of sea surface elevations $\chi(k)$, obtained from data of different measurement methods, is shown in **Figure 4**. The spectra are constructed by averaging over six realizations. The analysis of **Figure 4** indicates a good correspondence of the wave spectra obtained by different methods in the short-wave range of wavelengths ($\Lambda = 0.04\text{--}1.0$ m). The character of the obtained spatial spectra of the elevations testifies to the possibility of their power-law approximation by the Toba formula [23], recalculated taking into account the dispersion relation (12).

To generalize the data obtained, such characteristics of the spectra as the exponents of power approximation and the dispersion of wave energy in different wavelength ranges were analyzed. For the wavelength range $\Lambda = 1.0\text{--}5.0$ m, wave spectra were used, which were determined from the space image obtained from the GEOEYE satellite by the nonlinear recovery approach. For shortwave waves ($\Lambda = 0.04\text{--}1.0$ m), experimental data obtained in six experiments of the third type by three methods in two bands were used: $\Lambda = 0.04\text{--}0.4$ m and $\Lambda = 0.1\text{--}1.0$ m.

For comparison with known literature data, the parameters of wave spectra were calculated from the well-known approximations: Phillips, Pierson-Moskovitz, Toba, Leikin, and Rosenberg [19]. The values of the variances and exponents of power approximations of the spatial spectra of sea surface elevations, obtained experimentally by various methods, as well as obtained from known approximations, were analyzed in [19].

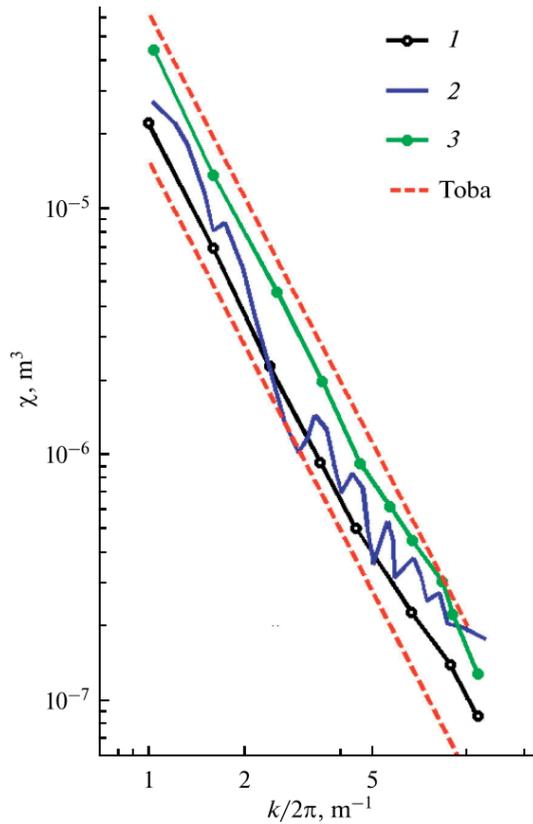


Figure 4. Spatial spectra of sea surface elevations, obtained by different methods: (1) retrieving of images by the nonlinear multiposition method; (2) contact measurements by a string wave; (3) stereo-photogrammetric measurements; red lines denote Toba approximation.

Analysis of the experimental data has shown that there is a coincidence of statistical estimates of the characteristics of sea waves measured by different methods within the mean square scatter of samples of these parameters. This indicates that the developed remote methods sufficiently accurately determine the characteristics of sea waves.

The most important for practice is the determination of the exponent p in power approximation. An analysis of the data obtained in the experiments shows that the parameters of the spectra of waves retrieved from the image spectra correspond best to the Toba approximation [23].

The obtained results of the studies by remote methods made it possible to reveal the following values of the parameters p for the experimental conditions:

$p = 2.22 \pm 0.08$ for the wavelength interval $\Lambda = 1.0\text{--}5.0$ m; $p = 2.23 \pm 0.09$ for the short-wavelength wavelength interval $\Lambda = 0.1\text{--}1.0$ m; $p = 2.1 \pm 0.08$ for the short-wavelength wavelength interval $\Lambda = 0.04\text{--}0.4$ m.

To determine the effect of sea surface disturbances associated with the nonstationary nature of the wave, correlation analysis was used to obtain the estimates. Correlation coefficients between sea surface characteristics in the short-wave range were studied in [19].

The correlation of the estimates carried out by various methods is quite high, and averages were 0.8–0.9. Those cases in which there is a decrease in the correlation coefficient are explained by the peculiarities of the measurement methods. For example, a slight decrease in the correlation coefficient of estimates of the exponent α obtained by the contact method, with estimates obtained from the images, is due to the time diversity of the registration of the spectral density at different frequencies ω . During the tuning of the filter transmission frequency, a change in the spectral density of the wave at different frequencies ω can occur, which leads to a deviation in the estimate of the exponent of the elevation spectrum with respect to estimates obtained for a fixed time in image processing [22].

Good correlation between independently measured wave spectra allows us to conclude that the developed remote measurement methods reliably reflect real processes in the ocean-atmosphere boundary layer.

Retrieving operators constructed by the numerical method and having passed the calibration procedure using contact data were used for experimental studies in various water areas [16, 18–20].

One of the important experiments was to study the development of wind waves at various distances from the shore. An experiment of this type was conducted in the water area of Mamala Bay near the Oahu Island (Hawaii, USA) [19].

Figure 5 shows four fragments of the space image obtained by the QuickBird satellite with 0.65 m spatial resolution, and the spectra of slopes retrieved on their base.

An analysis of the two-dimensional retrieved slope spectra shows that, as the distance from the coast and the wind regime change, characteristic additional wave systems develop. At the same time, the energy of sea waves increases with the distance from the coast and the increase in wind speed.

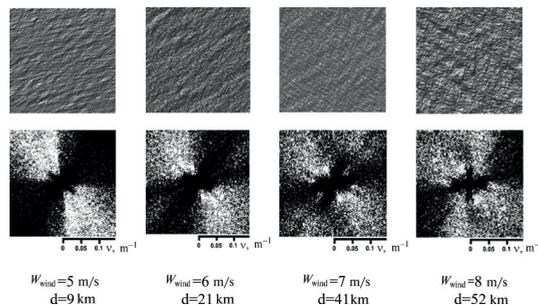


Figure 5. Fragments of the satellite image obtained at various distances from the shore in the water area of Mamala Bay off the Oahu Island and retrieved two-dimensional spatial spectra of sea wave slopes.

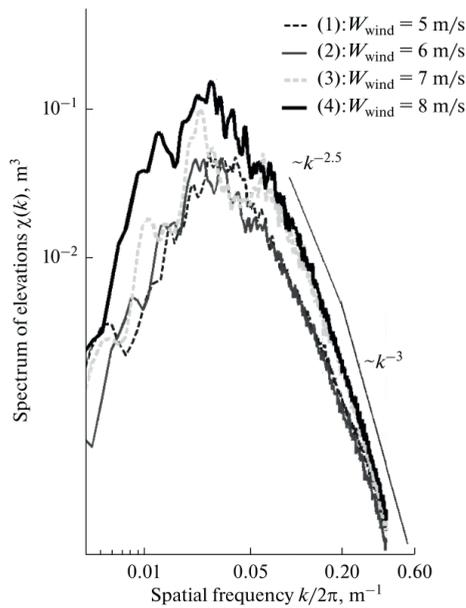


Figure 6. One-dimensional spatial spectra of sea wave elevation, retrieved from fragments of the satellite image, obtained at different distances from the shore at different wind speeds in the water area of Mamala Bay near Oahu (Hawaii, USA).

Figure 6 presents one-dimensional spatial elevation spectra obtained by averaging over the direction of two-dimensional spatial spectra of elevations in the 70° angular sector, recovered using the developed retrieving operator.

The analysis of **Figure 6** shows that the course of one-dimensional spectra retrieved from the two-dimensional spatial spectra of fragments of the satellite image depends on wind speed and the distance of the corresponding sections from the shore. The shape and position of the spectral maxima depends not only on the speed of the near-surface wind but also on the acceleration from the leeward shore, which in this experiment was between 10 and 50 km.

5. Conclusion

A method is developed to retrieve the spectra of gradients and elevations of sea waves from the spectra of aerospace optical images over a wide frequency range, based on the formation of a retrieving operator that takes into account the nonlinear character of the modulation of the brightness field by sea surface slopes.

The conducted studies demonstrated the effectiveness and adequacy of the application of the method of recovering the spectra of gradients and elevations of sea waves from satellite optical images of high spatial resolution.

The optimal parameters of such a retrieving operator are determined by an iterative method when comparing the spectra of aerospace images with spectra with sea wave characteristics measured with high accuracy by string waveforms under controlled conditions.

During the research, the spatial spectral characteristics of sea waves estimated from remote sensing data were compared with the corresponding characteristics measured by contact means under controlled conditions. The satellite data used for the comparison were the arrays of string wave recorders mounted on a stationary oceanographic platform, the data of a stereo survey performed with a high spatial resolution from a low altitude above the sea surface, as well as data of drifting wave buoys. Comparison of the spectra of waves and their statistical characteristics demonstrated the consistency of the results obtained in the processing of satellite images of high spatial resolution and the results of processing data obtained by various sea truth assets.

Experiments carried out in different water areas demonstrated the possibility of using a retrieving operator with optimal values of parameters found under certain conditions for obtaining satellite optical images of the sea surface for a wide range of wave formation conditions.

As a result of the application of numerical optimization procedures, the values of the parameters of nonlinear retrieving filters that are effective in both developed and developing waves, as well as in the presence of swell waves, are chosen. In this case, the measurement of the divergence of the wave spectra obtained from satellite images of high spatial resolution and subsatellite data at optimal values of these parameters is 0.08–0.12. This testifies to the adequacy of the proposed method for recording wave spectra from the spectra of satellite images over a wide frequency range.

Thus, the adequacy of remote measurement of both the time-averaged spectra of the sea surface and the variations of these spectra caused by wave nonstationarity using high spatial resolution images and nonlinear recovering operators has been experimentally confirmed. The conducted researches made it possible to develop methods and technologies for comprehensive ground-space monitoring of marine areas to obtain such important oceanographic characteristics as surface wave spectra.

The developed method can be used to study surface wave conditions, including in the space monitoring of natural and anthropogenic impacts on the marine waters.

Acknowledgements

The work was carried out with the financial support of the state represented by the Ministry of Education and Science of the Russian Federation in the framework of the Federal Program “Research and development in priority areas of development of the scientific and technological complex of Russia for 2014-2020” (unique identifier of the project RFMEFI57716 X0234).

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