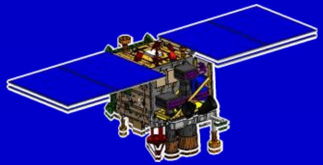
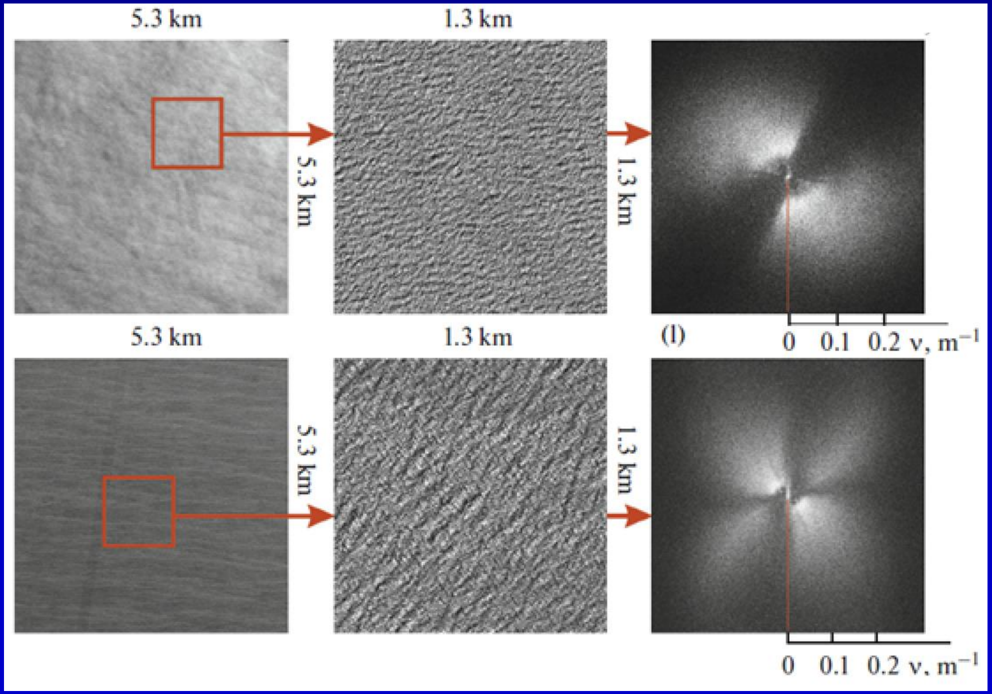
MEASUREMENT OF SEA WAVE SPATIAL SPECTRA FROM HIGH-RESOLUTION OPTICAL AEROSPACE IMAGERY

A.MURYNIN

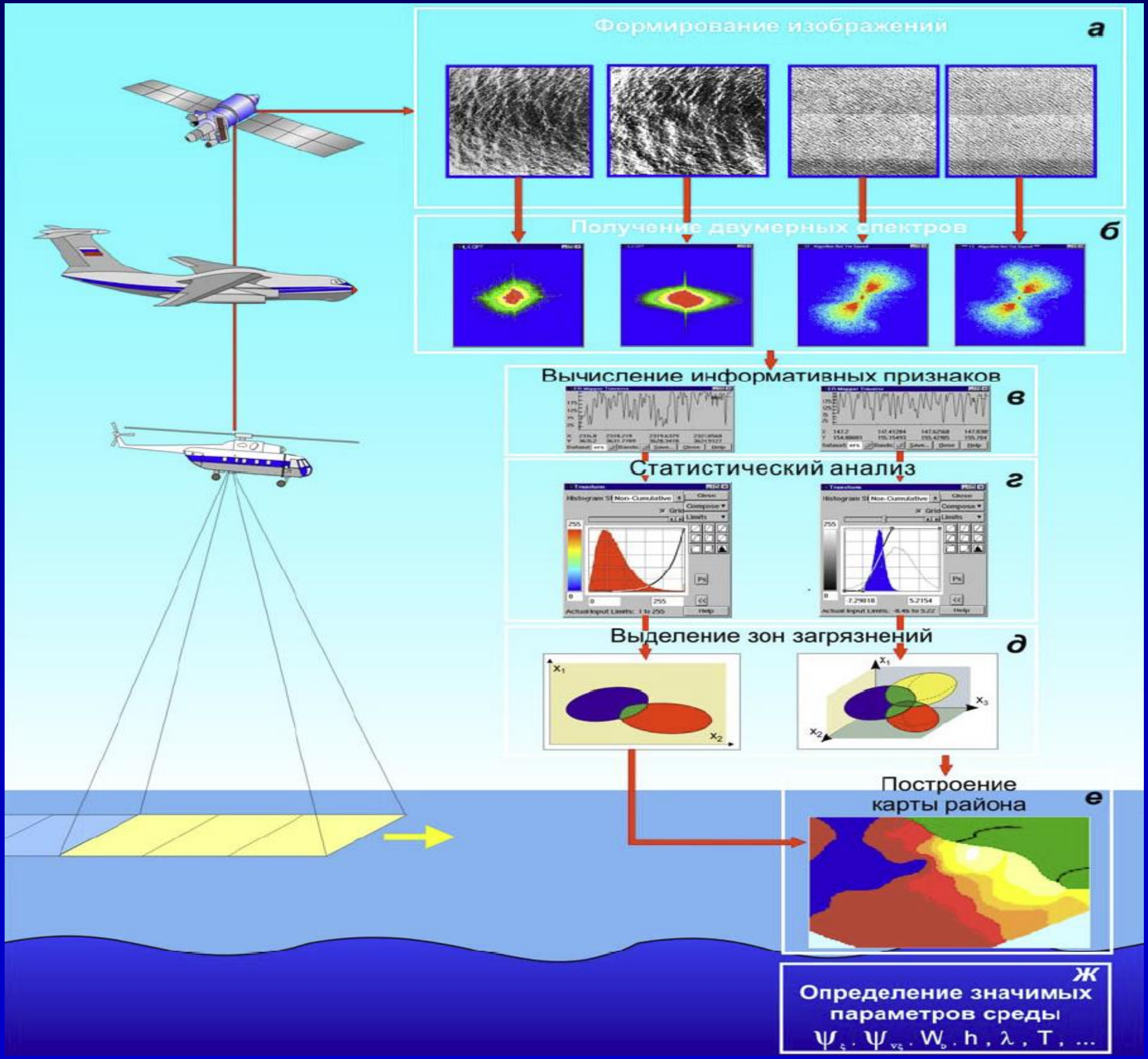


APPROACH TO STUDY OF SEA WAVES SPECTRA

Spatial and frequency wave spectra characterize the spatiotemporal structure of randomly changing ocean surface.
These spectra provide important information about different processes and phenomena that occur on the surface and in the near-surface layers of sea and oceans, about the energy properties of sea waves, and the parameters of the surface air layer and wind regime.
They also allow the detection of zones of adverse natural and anthropogenic impacts on the water environment and indication of emergency situations in the ocean.



SPATIAL FREQUENCY SPECTROMETRY

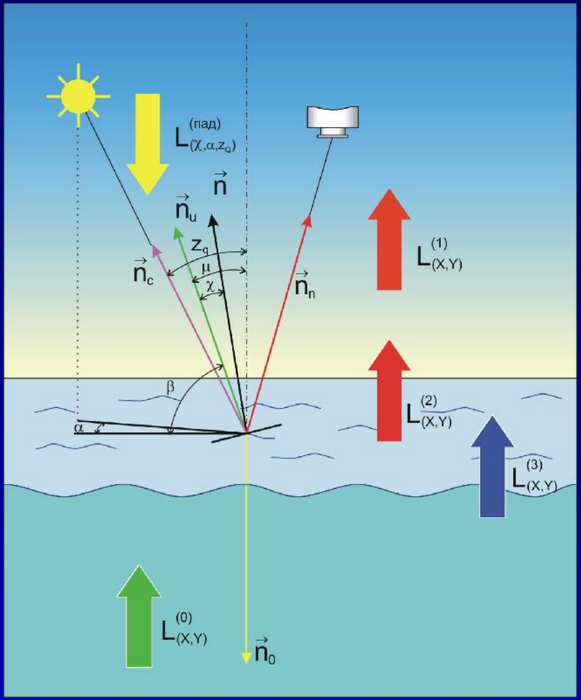


PHYSICS OF THE METHOD OF RESTORATION OF THE WAVE SPECTRA FROM SPECTRA OF OPTICAL IMAGES

The brightness of the radiation recorded by the remote equipment at small angles of the field of view

$$L(x,y) = L^{(1)} + \left[L^{(2)}(x,y) + L^{(3)}(x,y)\right]\tau_a \quad (*)$$

$L^{(1)}$ – The luminance component associated with scattering in the atmosphere in the direction of the receiver;
$L^{(2)}(x, y)$, $L^{(3)}(x, y)$ – Luminance components associated with surface reflection and water column scattering;
τ_a - Atmospheric transmission function



formation of the brightness field of the sea surface

Expanding (*) at each point of the (x, y) plane in a Taylor series in powers of the gradients (slopes) of the surface

$$\xi_x(x,y) = \frac{\partial \xi(x,y)}{\partial x}, \quad \xi_y(x,y) = \frac{\partial \xi(x,y)}{\partial y}$$

We obtain

$$L(x,y) = L^{(1)} + \left[L_0(x,y) + L_1(x,y)\xi_x(x,y) + L_2(x,y)\xi_y(x,y) + L_H(x,y)\right]\tau_a$$

$L_0(x,y)$ - Luminance component that does not depend on slopes;

$L_1(x,y)\xi_x(x,y)$ и $L_2(x,y)\xi_y(x,y)$ - Fluctuation components;

$L_1(x,y), L_2(x,y)$ - functions depending on lighting conditions;

L_H - Nonlinear component of brightness.

DEFINITION OF RECOVERY OPERATOR

$$L(x,y)=C_x\xi_x(x,y)+C_y\xi_y(x,y)+N'\left(x,y,\xi_x(x,y),\xi_y(x,y)\right)$$

From spectra of images $S(k_x,k_y)$ spectra of slopes $\Psi_\phi(k_x,k_y)$ can be obtained

$$\Psi_\varphi(k_x,k_y)=R(k_x,k_y)S(k_x,k_y)$$

$\Psi_\varphi(k_x,k_y)$ **- Two-dimensional slope spectrum;**

$R(k_x,k_y)$ **- Operator, depending on lighting and observation conditions, characteristics of remote equipment**

In the linear approximation (*N=const*) : $R(k_x,k_y)=const$

In the general case, to obtain wave spectra it is necessary to take into account nonlinear effects that play an appreciable role in the formation of images

The definition of a non-linear restoring operator is the task.

NUMERIC SIMULATION AND IMAGE PROCESSING ALGORITHMS

NUMERIC SIMULATION

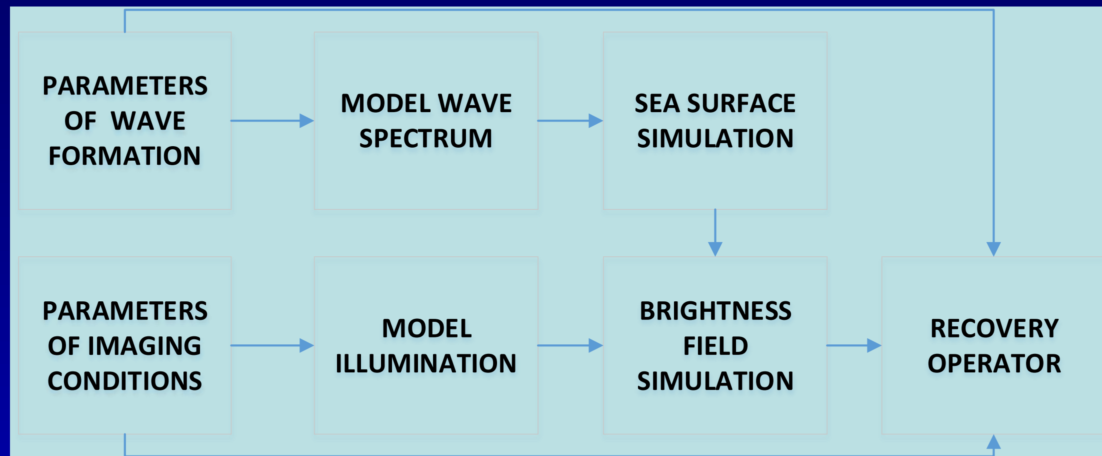
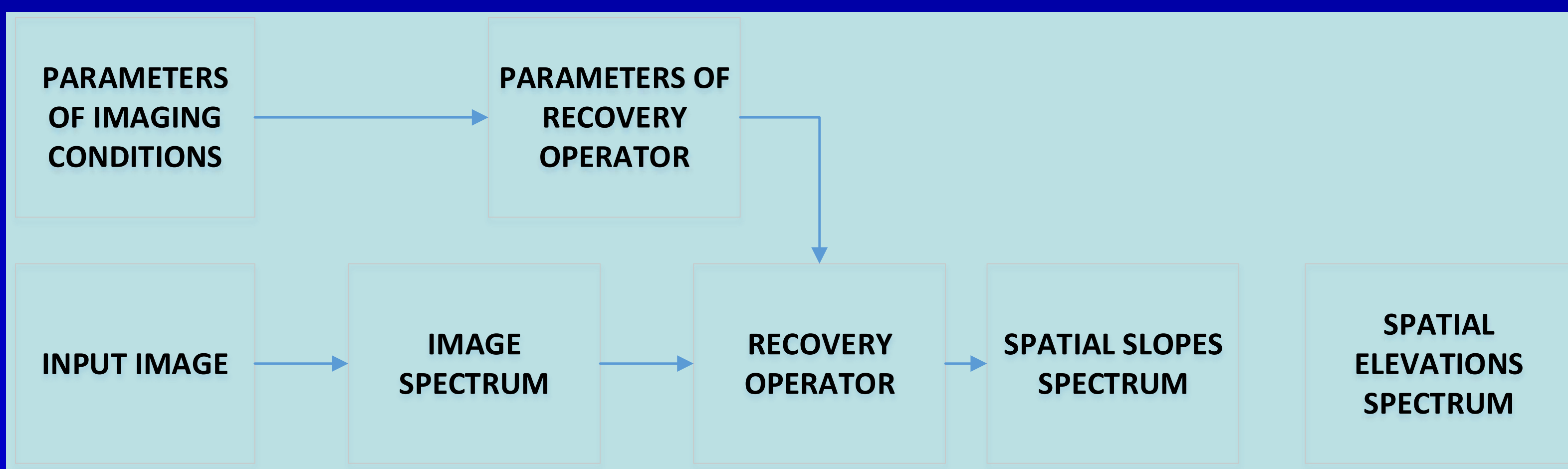
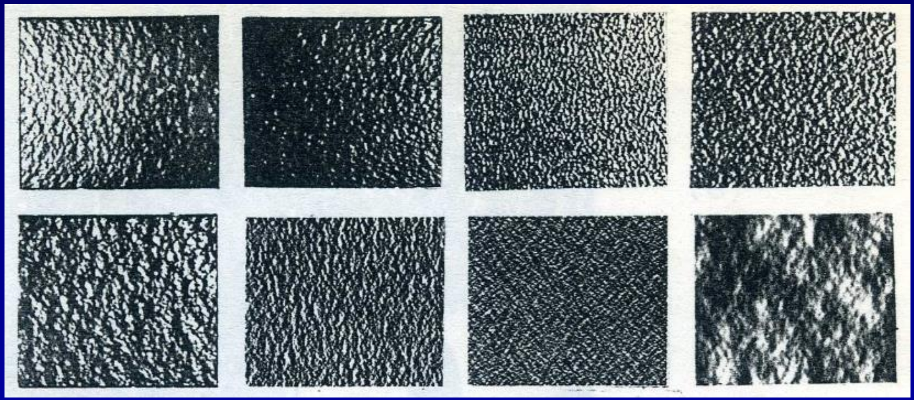


IMAGE PROCESSING

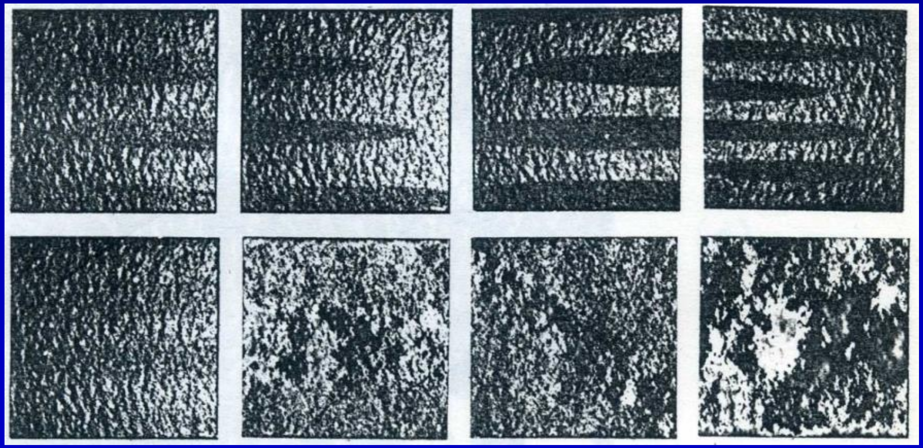


MODELING OF IMAGES OF THE SEA SURFACE

Background surface



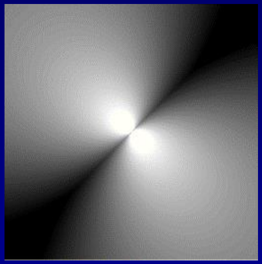
Phenomena on Sea Surface

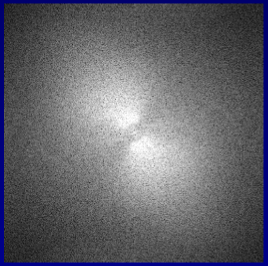


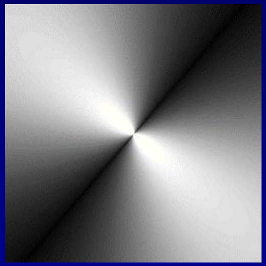
NUMERICAL SIMULATION AND CONSTRUCTION OF THE RECOVERY OPERATOR

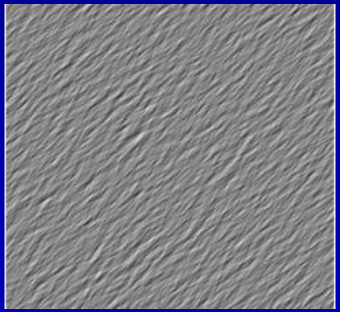
MODEL SPECTRUM

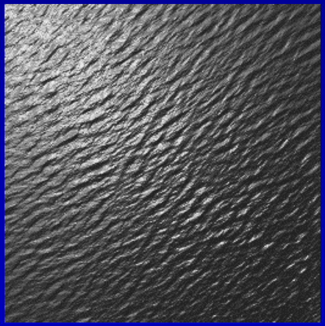
$$\Phi_G(\mathbf{k})$$











$$R(\mathbf{k}) = \frac{\Phi_G(\mathbf{k})}{S_M(\mathbf{k})}$$

THE SPACE-FREQUENCY FILTER IS FORMED IN THE FORM OF THE RATIO OF THE SEA SURFACE SLOPE SPECTRUM SYNTHESIZED BY THE NUMERICAL METHOD TO THE SPECTRUM OF THE MODEL OPTICAL IMAGE OBTAINED UNDER GIVEN CONDITIONS FOR THE FORMATION OF THE BRIGHTNESS FIELD

RECOVERY OF SEA SURFACE SPECTRA

TO OBTAIN THE SPECTRA OF SURFACE WAVES FROM THE SPATIAL SPECTRA OF AEROSPACE IMAGES, RESTORING OPERATORS MUST BE USED, WHICH ARE BUILT ON THE BASIS OF ALGORITHMS THAT TAKE INTO ACCOUNT THE VARIOUS CONDITIONS FOR THE FORMATION OF IMAGES AND THE CHARACTERISTICS OF THE EQUIPMENT.

$$\Psi_{\xi}(\mathbf{k}) = \frac{\sum_{m=1}^{M} \mathrm{R}^{(m)}(\mathbf{k}) S^{(m)}(\mathbf{k})}{\sum_{m=1}^{M} (\cos \varphi_C^{(m)} k_x + \sin \varphi_C^{(m)} k_y)^2}$$

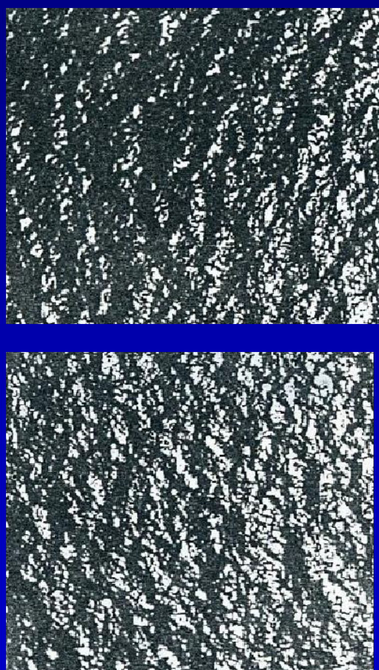
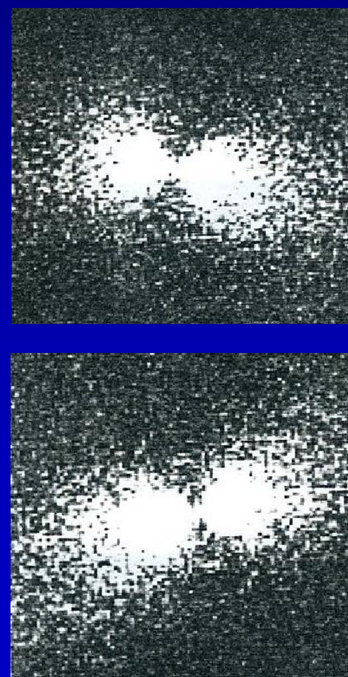


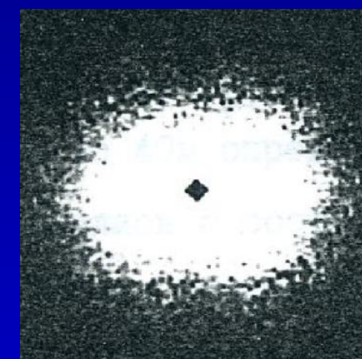
Image fragments recorded in different conditions



Spectra of image fragments

R

Spectra of sea surface slopes



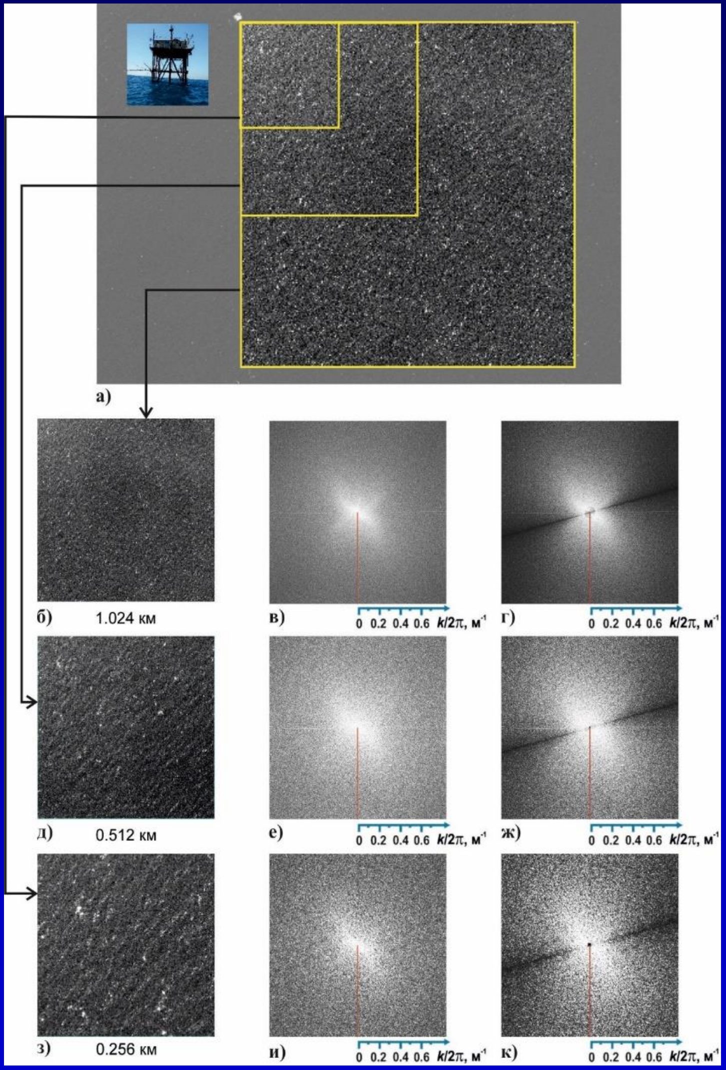
Spectrum of sea surface elevations

EXPEIMANTAL STUDY OF SEA WAVES SPECTRA

TYPES OF EXPERIMENTS

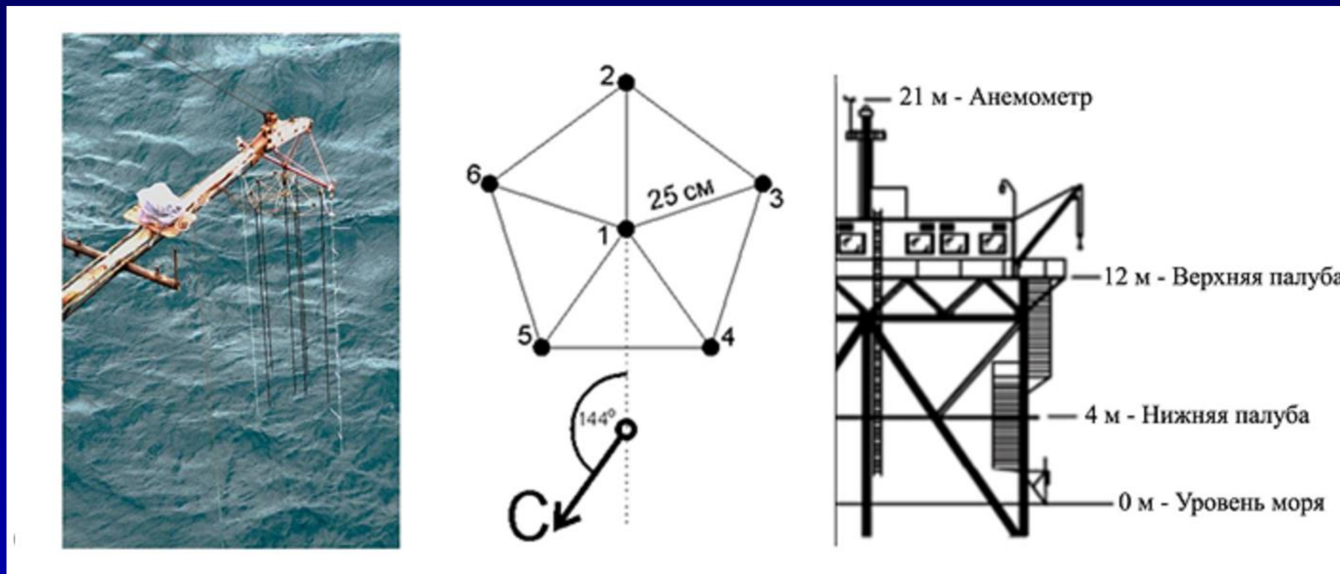
- **SPACE SHOOTING AND SYNCHRONOUS SUBSTITUTE MEASUREMENTS OF THE SPECTRA OF WAVE IN THE DISTRICT OF THE STATIONARY OCEANOGRAPHIC PLATFORM**
- **RESEARCHES IN THE SWITCH-WAVE AREA OF SPECTRA OF WAVE (Λ = 0.04-1.0 M) WITH STRONG WAVES, OBJECTIVE SHOOTING AND STEREO PHOTO FROM THE DECK OF THE OCEANOGRAPHIC PLATFORM**
- **SATELLITE RECORDING OF THE INVESTIGATED AQUATORIA AND SIMULTANEOUS MEASUREMENTS OF THE SPECTRA OF WAVE WITH THE AID OF DRIFTING WAVE BUEVES**
- **RESEARCHES IN AQUATORIES EXPOSED TO INTENSIVE ANTHROPOGENIC IMPACTS**

RECOVERY OF WAVE SPECTRA ON SATELLITE IMAGES



RESULTS OF SPATIAL SPECTRAL PROCESSING OF SATELLITE IMAGE OBTAINED ON SEPTEMBER 24, 2015 FROM FROM GEOEYE SATELLITE IN THE OCEANOGRAPHIC PLATFORM AREA

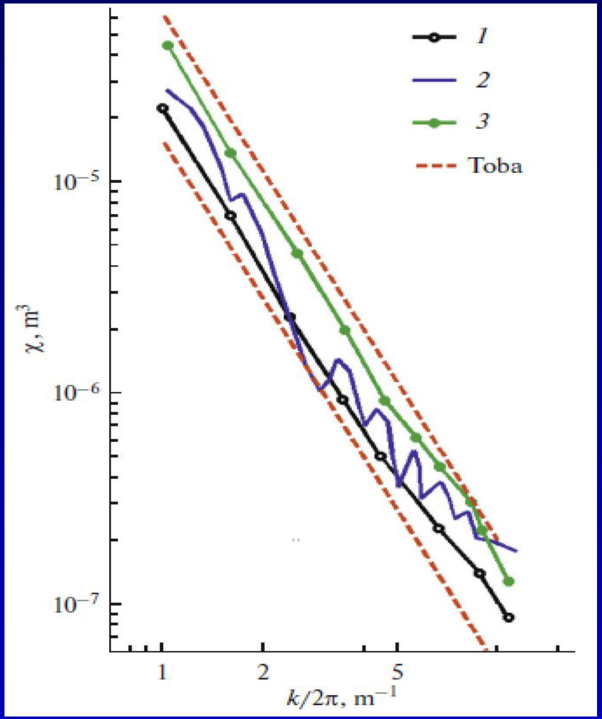
GROUND-TRUTH MEASUREMENTS OF THE WAVE SPECTRA



AEQUIPMENT ON THE OCEANOGRAPHIC PLATFORM IN KATSIVELI (CRIMEA)

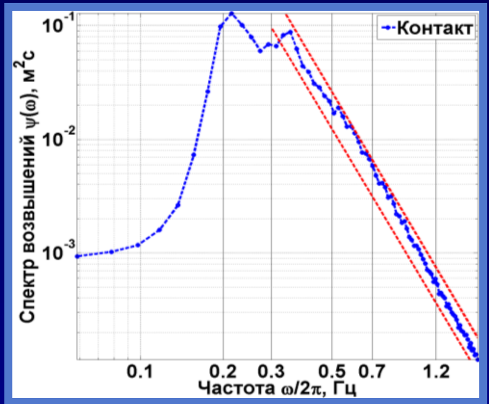
INVESTIGATED SEA AREA

RESULTS OF EXPERIMENTAL STUDIES

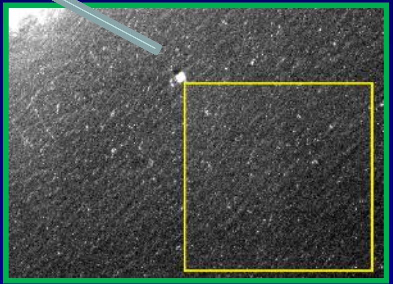


Spectra of elevations of the sea surface, obtained by different methods: 1 - recovery from images by a nonlinear multiposition method; 2 - contact measurements by a string wave recorder; 3 - stereophotogrammetric measurements; Red lines - Toba approximation (Toba, 1973).

EXPERIMENTAL STUDIES

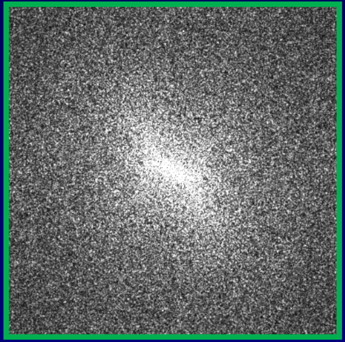


FREQUENCY SPECTRUM OF ELEVATIONS $\psi_{конт}(\omega)$ FROM CONTACT WAVERECORDER



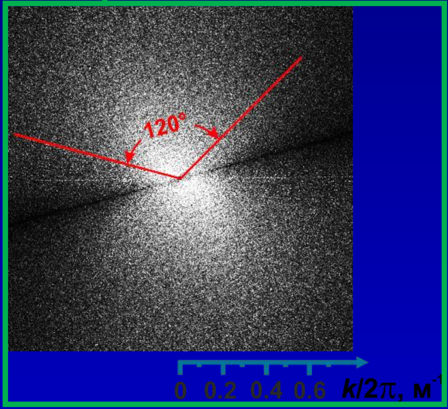
SATELLITE IMAGE

IMAGE SPATIAL SPECTRUM *S(k)*



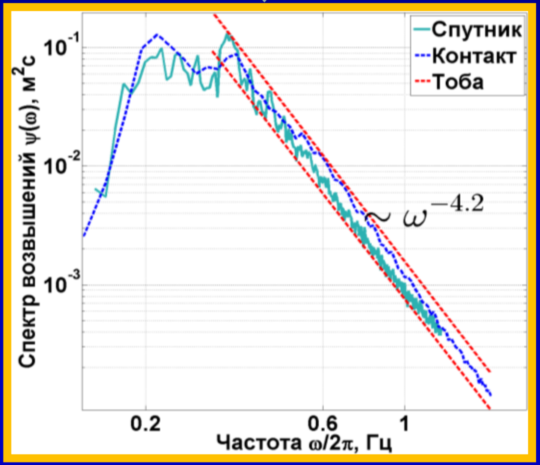
SLOPES SPECTRUM

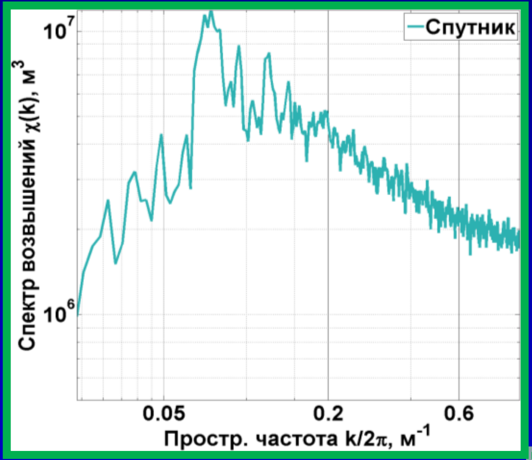
$\Phi(k,\theta) = R(k,W)\, S(k)$



ELEVATIONS SPECTRUM

$$\chi(k) = \int \Phi(k,\theta)\, d\theta$$





MEAN DEVIATION

$$\Delta = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(1-\frac{\psi_{cn}(\omega_n)}{\psi_{mo\delta}(\omega_n)}\right)^2} \approx 0.07$$

Спектр Тоба ~ω-4

CONVERSION TO FREQUENCY SPECTRUM USING DISPERSION RELATION

$$\psi_{cn}(\omega) = \chi(k(\omega))\frac{dk(\omega)}{d\omega}$$

$$\omega^2 = gk$$

RECOVERY OPERATOR *R(k,W)* получен OBTAINED BY NUMERICAL SIMULATION WITH WIND SPEED 11 m/s;
SUN ZENITH ANGLE AND AZIMUTH
46° , 165°

ANALYSIS OF THE RESULTS

Correlation coefficients between estimates of wave parameters σ_ξ and p_x by data of different techniques in the short wavelength range ($\Lambda = 0.04$–1.0 m)

Parameter estimated	Technique compared		Correlation coefficient, wavelength range Λ, m	
			Λ: 0.1–1.0	Λ: 0.04–0.4
σ_ξ	Nonlinear retrieval from images	String-wave recorder array	0.73	0.91
	Nonlinear retrieval from images	Stereophotography	0.79	0.78
	Stereophotography	String-wave recorder array	0.95	0.93
p_x	Nonlinear retrieval from images	String-wave recorder array	0.89	0.64
	Nonlinear retrieval from images	Stereophotography	0.65	0.93
	Stereophotography	String-wave recorder array	0.86	0.86

$$r^{(\alpha,\beta)} = \sum_{n=1}^{N}\left(\eta_n^{(\alpha)} - \overline{\eta}^{(\alpha)}\right)\left(\eta_n^{(\beta)} - \overline{\eta}^{(\beta)}\right) \Big/ \left(\sum_{n=1}^{N}\left(\eta_n^{(\alpha)} - \overline{\eta}^{(\alpha)}\right)^2 \sum_{n=1}^{N}\left(\eta_n^{(\beta)} - \overline{\eta}^{(\beta)}\right)^2\right)^{1/2}$$

$$\sigma_\xi = \sqrt{\int_{k_1}^{k_2} \chi(k)\, dk}.$$

$$\chi(k) = a_\chi k^{-p_\chi}$$

ANALYSIS OF THE RESULTS

Parameters of the sea-surface elevation field from data of comprehensive experiments and well-known approximations.

Data source	Parameters of spatial sea-surface elevation spectra				
	standard deviation σ_ξ, mm		exponent p_x		
	$\Lambda = 0.04–0.4$ m	$\Lambda = 0.1–1.0$ m	$\Lambda = 0.04–0.4$ m	$\Lambda = 0.1–1.0$ m	$\Lambda = 1.0–5.0$ m
Comprehensive experiment					
Nonlinear retrieval from images	3.1 ± 0.7	7.8 ± 1.3	2.12 ± 0.08	2.23 ± 0.09	2.22 ± 0.08
Stereophotography	5.4 ± 1.5	11.3 ± 2.7	2.10 ± 0.10	2.20 ± 0.17	no data
String-wave recorder array	3.8 ± 0.05	8.5 ± 1.7	$1.93 + 0.11$	1.98 ± 0.05	2.25 ± 0.05
Well-known approximations					
Phillips (Phillips, 1980)	3.5	8.6	3.0	3.0	3.0
Pierson–Moskowitz (Pierson and Moskowitz, 1964)	2.8	7.1	3.0	3.0	3.0
Toba (Toba, 1973)	3.7	7.3	2.5	2.5	2.5
Leikin and Rosenberg (Leikin and Rosenberg, 1987)	3.3	7.0	2.6	2.6	2.6

OPTMIZED RECOVERY OPERATOR

MODIFIED RECOVERY OPERATOR REPRESENTED IN THE SUPERPOSITION OF TWO OPERATORS

$$\mathbf{R}_{\mathrm{mod}}(\mathbf{k}) = \mathbf{R}_{\mathrm{low}}(\mathbf{k})\ \mathbf{R}_{\mathrm{high}}(\mathbf{k})$$

$\mathbf{R}_{\mathrm{high}}$ **HIGH-FREQUENCY RECOVERY OPERATOR**

$\mathbf{R}_{\mathrm{low}}$ **LOW-FREQUENCY RECOVERY OPERATOR**

$$\mathbf{R}_{high}(\mathbf{k}) = \mathrm{a}_0 \left(\cos(\varphi - \varphi_C)^{\mathrm{a}_3}\ \mathrm{k}^{-(\mathrm{a}_1 + \mathrm{a}_2 \cos(\varphi - \varphi_C))} \right)$$

$$\mathbf{R}_{\mathrm{low}}(\mathbf{k}) = \exp\left(\mathrm{a}_4 \mathrm{k}^{a_5} \right)$$

HIGH-FREQUENCY RECOVERY OPERATOR

COMPARISON WITH CONTACT DETAILS INCLUDES THE FOLLOWING OPERATIONS: TRANSITION TO ONE-DIMENSIONAL SPATIAL SPECTRUM

$$\chi^{дист}(k)=C\iint\Psi(k,\varphi)kdkd\varphi$$

TRANSITION TO FREQUENCY SPECTRUM

$$\omega^2=gk$$

$$\psi_{low}^{дист}(\omega)=\chi_{low}^{дист}(k)\frac{2\omega}{g}.$$

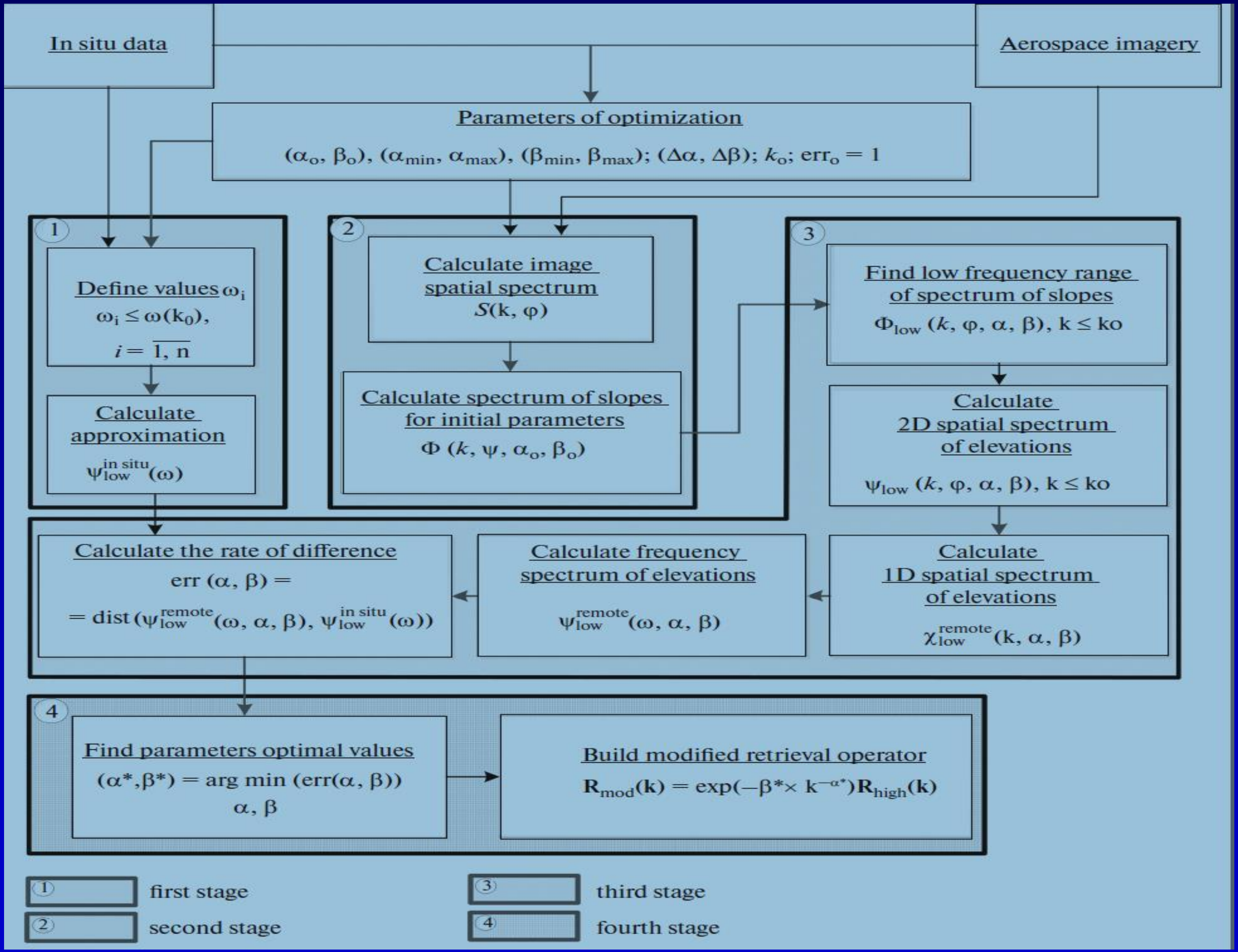
CALCULATION OF THE DIFFERENCE OF SPECTRA

$$\mathrm{dist}\left(\psi_{low}^{дист}(\omega),\psi_{low}^{конт}(\omega)\right)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\psi_{low}^{дист}(\omega_i)-\psi_{low}^{конт}(\omega_i)}{\psi_{low}^{конт}(\omega_i)}\right)^2}$$

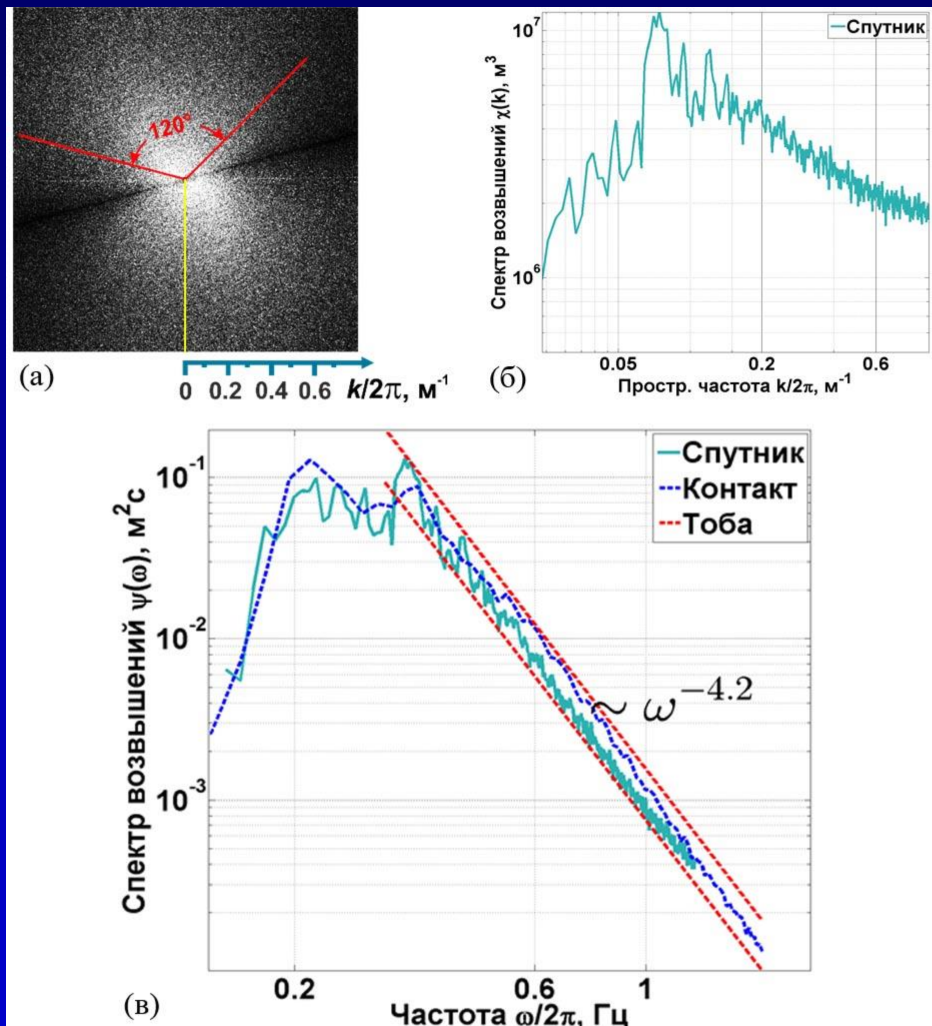
FINDING OPTIMAL VALUES OF PARAMETERS

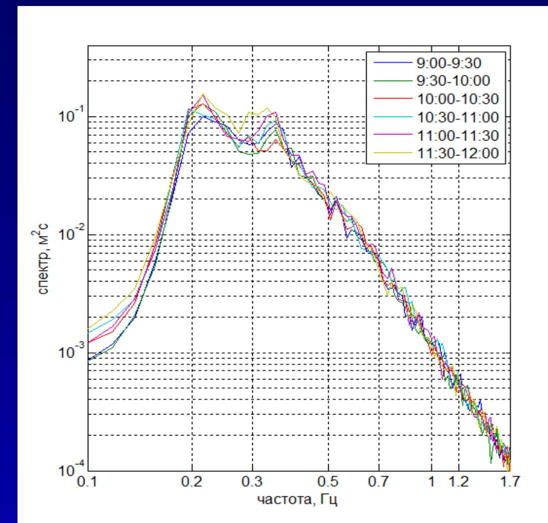
$$\left(\alpha^*,\beta^*\right)=\arg\min_{\alpha,\beta}\mathrm{dist}\left(\psi_{low}^{дист}(\omega),\psi_{low}^{конт}(\omega)\right)$$

SCHEME FOR CONSTRUCTING A MODIFIED RECOVERY OPERATOR

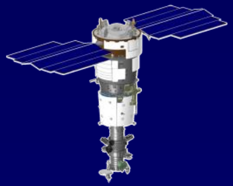


COMPARISON OF SPECTRA OF WAVE ON REMOTE CONTACT DATA



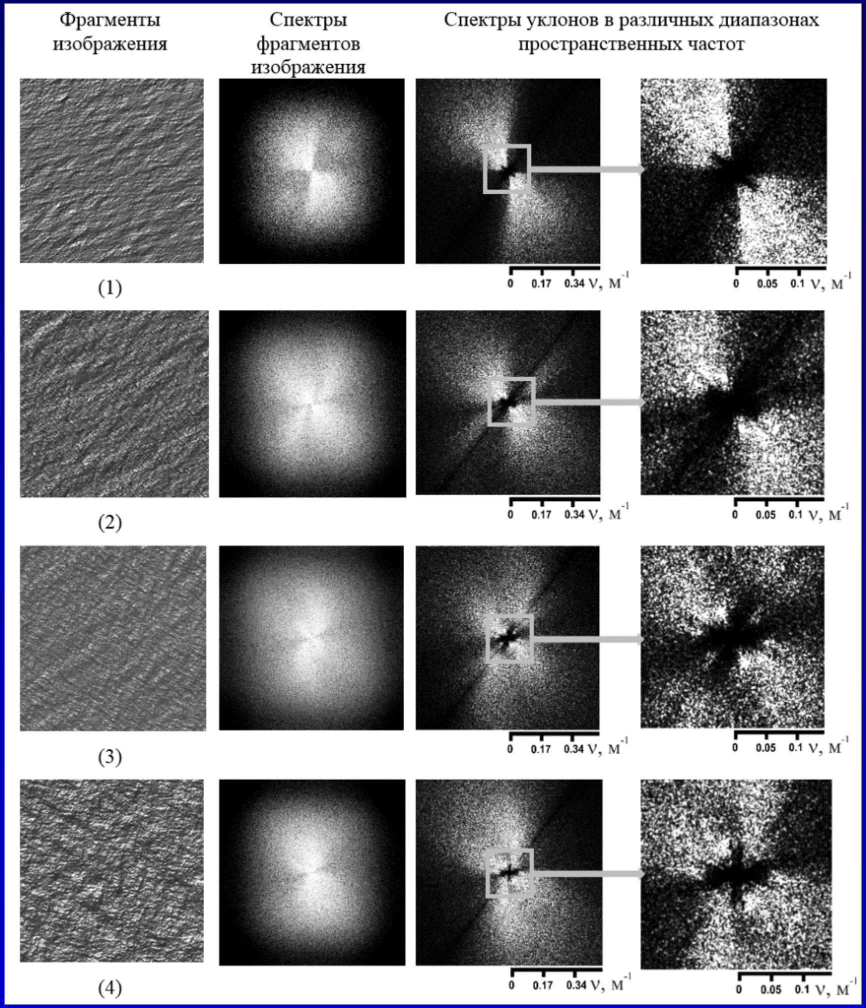


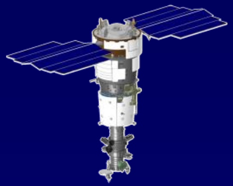
COMPARISON OF THE SPECTRA OF SEA WAVES MEASURED BY SATELLITE AND CONTACT DATA, AND WITH TOBA APPROXIMATION



RESULTS OF EXPERIMENTAL STUDIES

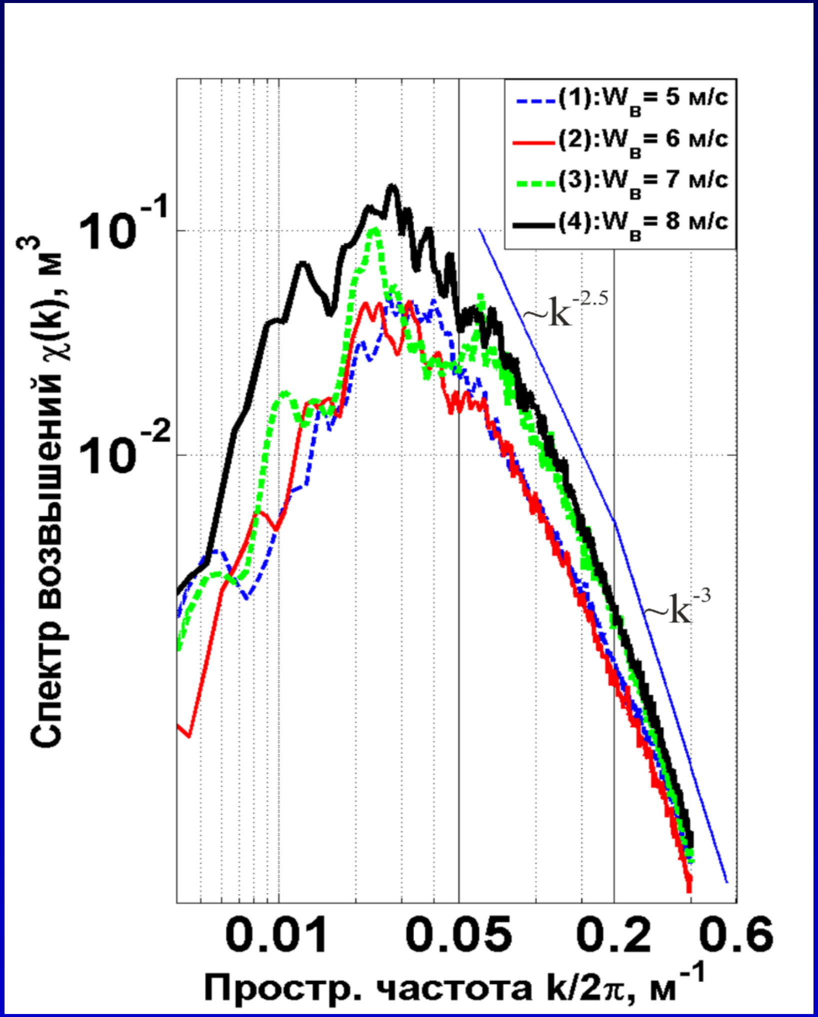
Fragments of the space image, obtained at various distances from the shore in the water area of Mamala bay off the island of Oahu. Two-dimensional spatial spectra of these fragments and recoverd two-dimensional spatial spectra of sea-wave slopes in two ranges of spatial frequencies





RESULTS OF EXPERIMENTAL STUDIES

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).



CONCLUSIONS

A method has been developed for the remote measurement of sea wave spectra from cosmic optical images, based on the use of restoring operators both at high and low spatial frequencies. An approach is proposed for tuning and validation of the developed method using data obtained from sub-satellite measurements performed by string waveguns. The study of sea wave spectra in a wide range of wavelengths using the spectra of satellite optical images of high spatial resolution (0.5-1.0 m) and measurement data from the oceanographic platform with the help of string wave recorders, a stereo system, and also with the help of floating wave buoys. A comparison of the spectra of waves reconstructed from space images and simultaneously obtained with the help of sub-satellite means is carried out. Analysis of the comparison results showed that correlation coefficients of the estimates performed by various methods averaged 0.8-0.9, which indicates the adequacy of the proposed methods. The exponents of power approximations of spatial spectra in the wavelength range 0.04 ... 5.0 m are established. It is shown that the wave spectra obtained experimentally by satellite and contact methods are best approximated by the Toba spectrum. The results of applying the proposed method for studying sea-wave spectra in different water areas and under various wave formation conditions are presented.

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Bondur V.G., Dulov V.A., Murynin A.B., Yurovsky Yu.Yu. **A study of sea-wave spectra in a wide wavelength range from satellite and in-situ data // Izvestia, Atmospheric and Oceanic Physics. 2016. Vol. 52. No. 9. P. 888-903. DOI: 10.1134/S0001433816090097.**

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THANK YOU FOR ATTENTION !

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