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SYNTHESIS OF THE OPTIMAL ALGORITHM AND STRUCTURE OF CONTACTLESS OPTICAL DEVICE FOR ESTIMATING THE PARAMETERS OF STATISTICALLY UNEVEN SURFACES

The production of parts and (or) finished products in electronics, mechanical engineering and other industries is inextricably linked with the control of the accuracy and cleanliness of the processed surfaces. Currently existing meters of parameters of statistically uneven surfaces, both contact and non-contact have some disadvantages, as well as limitations due to methods and design features of measurement. Speckle interferometric methods for measuring parameters of statistically uneven surfaces make it possible to get away from some disadvantages inherent in existing methods and measurements. The use of methods of statistical radio engineering, methods of optimization of statistical solutions and estimates of parameters of predictive distributions for optimal radio engineering system synthesis is promising for the analysis and processing optical-electronic coherent laser space-time signals (speckle images) form with the laser radiation scattered by statistically uneven surfaces. This work synthesizes the optimal algorithm and structure for analyzing the parameters of statistically-temporal surfaces based on spatio-temporal processing of optical speckle interference signals and images using modern methods of optimal synthesis of radio engineering and coherent optoelectronic systems. In this work, an algorithm for processing optical signals scattered by statistically uneven surfaces is synthesized and investigated for problems of optimal estimation of parameters and statistical characteristics of statistically uneven surfaces. A block diagram of the optical contactless device for evaluating the parameters of statistically uneven surfaces is proposed. The limiting errors of estimation parameters of statistically uneven surfaces and the optimal installation angles of the emitters and the optical receiver are investigated. Equations are obtained for estimating the root-mean-square height of the ridges and the correlation radius of small-scale statistically uneven surfaces in the approximation of small perturbations. The proposed method for evaluating the parameters of statistically uneven surfaces allows to increase the accuracy of measurements, to conduct a non-contact assessment of the parameters - even statistically uneven surfaces that have geometric surface irregularities or located in hard-to-reach places, for example, grooves, holes, as well as products of cylindrical, spherical and other shapes.

Keywords: *surface roughness; laser; speckle pattern; optimal algorithm; optical receiver; statistically uneven surfaces.*

Introduction

The problems of monitoring the parameters of statistically uneven surfaces (SUS) are very relevant in various fields of modern science and technology: metal-based manufacturing [1-2], remote sensing [3], robotics [4], tomography [5], microelectronic manufacturing [6], etc. In industry, mechanical engineering and production of parts and finished products at different stages of the technological process of their processing and manufacture, contact or bulky (not portable) optical meters are predominantly used. This fact is mentioned in [7,8]. Today, the creation of non-contact devices for assessing the parameters of SUS is in demand. At the same time, it is important to design them based on the synthesis of optimal algorithms for processing optical signals by statistical methods of optimal estimates of the measured parameters. Statistical theory of such systems synthesis was developed by V. E. Dulevich [9], V. D. Stepanenko [10], B. R. Levin [11], P. A. Bakut, and G. P. Tartakovskii [12], V. A. Kotel'nikov [13]. Application of such methods of optimization gives optimal structures of a measuring system and limit errors of parameters estimation.

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Objectives. In this work the optimal algorithm for processing optical signals scattered by SUSs and a block diagram of an optical contactless device for estimating the parameters of SUSs have to be developed and investigated.

Tasks. To reach the objectives it is necessary to solve following tasks:

– define models of the probe and scattered signals,

– investigate the statistical characteristics of the scattered signals taking into account parameters of the uneven surfaces,

– synthesize optimal signal processing algorithm,

– define structure of the optimal measuring system,

– derive analytical expressions for measurements limiting errors.

The article has the following **structure**: Section 1 is devoted to the observation equation and its statistical description, section 2 describes the process of the Optimal algorithm synthesis, section 3 shows the calculation of the limiting errors in the estimation of the measured parameters, section 4 shows the method of Optimal estimation of the parameters of a small-scale statistically uneven surface, in section 5 it was investigated ranges of viewing angles and calculation of the limiting errors of measurements of the parameters of small-scale SUS, final sections are conclusions and references.

The research results presented in the article were obtained as part of the implementation of the following joint projects by the authors: Ukrainian radar complex of low altitudes and flight speeds for helicopters of JSC "Motor Sich", Ultra-wideband microwave passive radar for the university nanosatellite KHAI-1KA and Helicopter (for Mi-2MSB-V, Mi-8MTV-MSB1, Mi-8MTV-V, Mi-24V-MSB) radar collision warning radar for low-altitude safety. These projects were obtained by the authors in the mentioned above institutions and were sponsored or would be sponsored by the Ministry of education and science of Ukraine.

Observation equation and its statistical description

The estimated parameters and statistical characteristics can be chosen as the root-mean-square heights and correlation radii of a statistically uneven surface, its dielectric indices, and other characteristics.

Estimation of the entire set of unknown parameters of statistically uneven surfaces included in the vector $\vec{\zeta} = \|\zeta_k\|$, requires an appropriate number of independent observation equations. The group of necessary equations can be formed by receiving signals at different polarizations, from several angular directions $\vec{\vartheta}$ using multiple wavelengths λ_m and etc.

In this case, we consider the observation equation as the sum of the useful signal and an additive noise. Useful signal has form of an interference field (speckle pattern) corresponding to the investigated statistically uneven surface To obtain the necessary system of equations it is used several wavelengths λ_m. The geometry of the problem is shown in Fig. 1, where 1, 2 are laser radiation sources with wavelengths λ_1 and λ_2, 3 is the investigated surface, 4 is the multi-element optical receiver. The desired parameters of the SUS are the correlation radius and the root-mean-square height of the irregularities. At the same time, it is necessary to take into account that today most of the optical receiver market is not single-element receivers, but multi-element ones, which are an array of point receivers. The receiving area of such a matrix will be considered as the field of point broadband receivers with small spatial angular dimensions. The set of signals observed in the plane at several frequencies can be represented as a vector

$$\vec{u} = \vec{s}\left(\vec{\zeta}\right) + \vec{n} = \left\| u_1\left(t,\vec{\vartheta},\lambda_1\right), u_2\left(t,\vec{\vartheta},\lambda_2\right), \ldots \right.$$
$$\left. \ldots, u_M\left(t,\vec{\vartheta},\lambda_M\right) \right\| = \left\| u_m\left(t,\vec{\vartheta},\lambda_m\right) \right\| \qquad (1)$$

where

$$t \in \left(0, T_m\right), \quad m = \overline{1, M},$$
$$\vec{s}\left(\vec{\zeta}\right) = \left\| s_m\left(t,\vec{\vartheta},\lambda_m,\vec{\zeta}\right) \right\|, \quad \vec{n} = \left\| n_m\left(t,\vec{\vartheta},\lambda_m\right) \right\|,$$
$$u_m\left(t,\vec{\vartheta},\lambda_m\right) = s_m\left(t,\vec{\vartheta},\lambda_m,\vec{\zeta}\right) + n_m\left(t,\vec{\vartheta},\lambda_m\right).$$

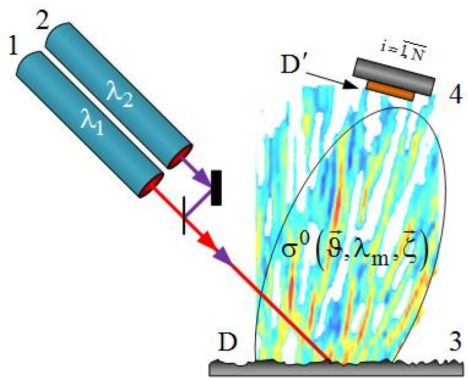

Fig. 1. Geometry of the problem of studying parameters of statistically uneven surfaces

Useful signal (speckle pattern) formed on the surface $\vec{r}' \in D'$ of the photosensitive elements of the optical receiver (OR) can be represented as a function of time t and angular coordinates $\vec{\vartheta}\left(\vec{r}'\right)$, uniquely related to coordinates $\vec{r}'$,

$$\vec{s}_m\left(t,\vec{\vartheta},\lambda_m,\vec{\zeta}\right) = \mathrm{Re}\left(\int_D \dot{F}_m\left(\vec{r},\vec{\zeta}\right) \times \right.$$
$$\left. \times \dot{A}_m\left[t - t_d\left(\vec{r},\vec{\vartheta}\right)\right] e^{j\omega_m\left[t - t_d\left(\vec{r},\vec{\vartheta}\right)\right]} d\vec{r} \right), \qquad (2)$$

where $\dot{F}_m\left(\vec{r},\vec{\zeta}\right)$ is the complex coefficient of scattering of the incident laser radiation by the elementary sections of the studied area of the SUS, $\vec{\zeta}$ is the surface parameters to be evaluated. The functional relationship of the $\vec{\zeta}$ with the scattering coefficient is shown here conditionally, since in this work the statistical parameters of the correlation function of the scattering coefficient will be subject to assessment. In (2) σ_h is the root-mean-square height of irregularities σ_h and L_h is the correlation radius, $\vec{\zeta} = (\sigma_h, L_h)$), $t_d\left(\vec{r},\vec{\vartheta}\right) = R\left(\vec{r},\vec{\vartheta}\right)/c$ is the delay time of the scattered optical radiation propagating at a distance $R\left(\vec{r},\vec{\vartheta}\right)$ from the elements of the investigated surface with coordinates $\vec{r} = \left(x, y\right) \in D$ to the receiving elements of the photosensitive device with angled $\vec{\vartheta}\left(r'\right)$ or their corresponding linear coordinates $\vec{r}' \in D'$, Fig. 1. $A_m\left(t\right)$ is the envelope of a serial of harmonic oscillations emitted by each individual electron at random times t. Its length in space determines the length of coherence. Vector of direction cosines

$$\vec{\vartheta} = \left\|\cos\theta_x, \cos\theta_y\right\| = \vec{\vartheta}_0 + \Delta\vec{\vartheta} \tag{3}$$

oriented to the elements of the optical receiver in the vicinity of the direction $\vec{\vartheta}_0$ to its center,

$$\Delta\vec{\vartheta} = \vec{r}'/L, \tag{4}$$

where L is the distance between the centers of the optical receiver and the illuminated area of the SUS; observation intervals T_m may be the same and may be different.

Using (4) in linear coordinates $\vec{r}' \in D'$ on the surface of the photosensitive device, this signal can be recorded in this form

$$\vec{s}_m\left(t, \vec{r}', \vec{\vartheta}_0, \lambda_m, \vec{\zeta}\right) = \mathrm{Re}\left(\int_D \dot{F}_m\left(\vec{r},\vec{\zeta}\right) \times \right.$$
$$\left. \times \dot{A}_m\left[t - t_d\left(\vec{r}, \vec{r}', \vec{\vartheta}_0\right)\right] e^{j\left[\omega_m t - k_m R\left(\vec{r},\vec{r}',\vec{\vartheta}_0\right)\right]} d\vec{r}\right), \tag{5}$$

where $k_m = \omega_m/c = 2\pi/\lambda_m$ – is the wavenumber.

Noise $n_m\left(t\right)$ is the white noise that can be caused by normal broadband lighting in the measurement room, as well as by the internal noise of the photosensitive recorder. We assume this interference to be spatio-temporal white noise with a correlation function of the following form

$$n_m\left(t_1, t_2, \vec{r}_1', \vec{r}_2'\right) =$$
$$= \left\langle n_m\left[t_1, \vec{\vartheta}_1\left(\vec{r}_1'\right)\right] n_m\left[t_2, \vec{\vartheta}_2\left(\vec{r}_2'\right)\right]\right\rangle =$$
$$= \frac{N_{0m}}{2}\delta\left(t_1 - t_2\right)\delta\left(\vec{r}_1' - \vec{r}_2'\right) \tag{6}$$

and power spectral density $N_{0n}/2$. Internal noise of the elements of the photosensitive recording device, located at separate discrete points $\vec{r}'$, are statistically independent and their description in the general case does not contradict formula (6).

It is assumed that at different wavelengths (frequencies of laser radiation) the processes $u_m\left(t\right)$ are Gaussian and independent from each other. The Gaussian nature of the random signal (2) and its complex amplitude is due to multiple reflections of vibrations from a statistically uneven rough surface. We find its correlation function in the form, that is specified in [14, 15],

$$R_{s_m}\left(t_1, t_2, \vec{r}_1', \vec{r}_2', \vec{\zeta}\right) = \left\langle s_m\left(t_1, \vec{r}_1', \vec{\vartheta}_0, \lambda_m, \vec{\zeta}\right) \times \right.$$
$$\left. \times s_m\left(t_2, \vec{r}_2', \vec{\vartheta}_0, \lambda_m, \vec{\zeta}\right)\right\rangle =$$
$$= \frac{1}{2}\mathrm{Re}\left(\int_D\int_D \left\langle \dot{F}_m\left(\vec{r}_1,\vec{\zeta}\right)\dot{F}_m\left(\vec{r}_2,\vec{\zeta}\right)\right\rangle \times \right.$$
$$\times \dot{A}_m\left[t_1 - t_d\left(\vec{r}_1, \vec{r}_1', \vec{\vartheta}_0\right)\right]\dot{A}_m^*\left[t_2 - t_d\left(\vec{r}_2, \vec{r}_2', \vec{\vartheta}_0\right)\right] \times$$
$$\left. \times e^{j\left\{\omega_m\left(t_1 - t_2\right) - k_m\left[R\left(\vec{r}_1,\vec{r}_1',\vec{\vartheta}_0\right) - R\left(\vec{r}_2,\vec{r}_2',\vec{\vartheta}_0\right)\right]\right\}} d\vec{r}\right). \tag{7}$$

The correlation radius of microroughness of the investigated surface is assumed to be small, i.e. reflection coefficient correlation function

$$R_{F_m}\left(\vec{r}_1, \vec{r}_2, \vec{\zeta}\right) = \left\langle \dot{F}_m\left(\vec{r}_1,\vec{\zeta}\right)\dot{F}_m\left(\vec{r}_2,\vec{\zeta}\right)\right\rangle \tag{8}$$

from them is narrow. The length of the envelope of the harmonic wave train $\dot{A}_m\left[t_1 - t_d\left(\vec{r}_1, \vec{r}_1', \vec{\vartheta}_0\right)\right]$, determining the coherence length of laser radiation is much larger than the width of the correlation function $R_{F_m}\left(\vec{r}_1, \vec{r}_2, \vec{\zeta}\right)$, as well as the linear dimensions of the area filled with the area of the light-sensitive matrix of the radiation detectors. In this case, changing the envelope $\dot{A}\left[t_1 - t_d\left(\vec{r}_1, \vec{r}_1', \vec{\vartheta}_0\right)\right]$ can be neglected when passing from coordinates $\vec{r}_1$, $\vec{r}_1'$ to coordinates $\vec{r}_2$, $\vec{r}_2'$. Then

$$\dot{A}\left[t_1 - t_d\left(\vec{r}_1, \vec{r}_1', \vec{\vartheta}_0\right)\right] \approx \dot{A}\left[t_1 - t_d\left(\vec{r}_2, \vec{r}_2', \vec{\vartheta}_0\right)\right] \approx$$
$$\approx \dot{A}\left[t_1 - t_d\left(\vec{r}, \vec{\vartheta}_0\right)\right].$$

Expanding in a Taylor series any of the terms of the distance difference in the exponent of formula (7) we get

$$\Delta R = R\left(\vec{r}_1, \vec{r}_1', \vec{\vartheta}_0\right) - R\left(\vec{r}_2, \vec{r}_2', \vec{\vartheta}_0\right) \tag{9}$$

in the vicinity of the values of the variables $\vec{r}_1$ or $\vec{r}_2$ by differences $\Delta\vec{r} = \vec{r}_1 - \vec{r}_2$ and limiting ourselves to the first linear terms of this series, which mainly take place within the narrow correlation function, and also following the methodology presented in [8, 14]. Taking into account (9) we obtain such an expression for the corre-

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lation function

$$R_{s_m}\left(t_1,t_2,\vec{r}_1',\vec{r}_2',\vec{\zeta}\right)=\frac{1}{2}\operatorname{Re}\Big\{e^{j\left[\omega_m(t_1-t_2)\right]}\times$$
$$\times\int_D \sigma^0\left(\vec{r},\vec{q}_\perp,\vec{\zeta}\right)\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]\times$$
$$\times\dot{A}_m^*\left[t_2-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]e^{j\Delta\vec{q}_\perp\Delta\vec{r}'}d\vec{r}\Big\}, \qquad (10)$$

where

$$\sigma^0\left(\vec{r},\vec{q}_\perp,\vec{\zeta}\right)=\int_D R_{F_m}\left(\vec{r},\Delta\vec{r},\vec{\zeta}\right)e^{j\vec{q}_\perp\Delta\vec{r}}\,d\Delta\vec{r}\Big) \quad (11)$$

$\sigma^0\left(\vec{r},\vec{q}_\perp,\vec{\zeta}\right)$ is the effective scattering cross section, that is studied in [16], $\vec{q}_\perp$ is the horizontal projection of scattering, used in works [16, 17], the components of which are the spatial frequencies of the scattering coefficient $\dot{F}_m\left(\vec{r},\vec{\zeta}\right)$, which indicates resonant (selective) scattering of waves on certain spatial spectral components of surface irregularities. If the surface roughness is a statistically homogeneous random process, then $\sigma^0\left(\vec{r},\vec{\zeta}\right)=\sigma^0\left(\vec{\zeta}\right)=\text{const}$.

It can be assumed that at the input of each element of the optical receiver matrix with coordinates $\vec{r}'$ (at $\vec{r}_1' = \vec{r}_2' = \vec{r}'$) the received radiation has the same time independent $\vec{r}'$ correlation functions, which have the following form

$$R_{s_m}\left(t_1,t_2,\vec{r}',\vec{\zeta}\right)=R_{s_m}\left(t_1,t_2,\vec{\zeta}\right)=\sigma_m^0\left(\vec{r},\vec{q}_\perp,\vec{\zeta}\right)\times$$
$$\times\frac{1}{2}\operatorname{Re}\Big\{e^{j\left[\omega_m(t_1-t_2)\right]}\int_D\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]\times$$
$$\times\dot{A}_m^*\left[t_2-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]d\vec{r}\Big\}. \qquad (12)$$

In this case that in the spatial coordinates $\vec{r}_1'$, $\vec{r}_2'$ the correlation function of the speckle pattern is determined by expression (10).

We will consider the sensitive area of an optical receiver. It is assumed that the receiving elements of the optical receiver (OR) are located perpendicular to the directions $\vec{\vartheta}_0$. Angle increments $\Delta\vec{\vartheta}$ within the receiving area, the OR are very small. The brightness of the interference speckle pattern is significant. Dozens and hundreds of interference maxima and minima are formed in the region of the matrix of the OR receiving elements, which have the form of light and dark spots, called speckles. This speckles are described and mentioned as the interference on the image at works [18, 19]. Their angular sizes are approximately equal to the angular correlation radius of the speckle pattern. This correlation radius is approximately equal to

$$\left|\delta\vec{\vartheta}\right|=\lambda_m/D_0\,, \qquad (13)$$

where D_0 spot diameter on the investigated area D, obtained by illuminating it with a laser beam.

The speckle pattern itself can be regarded as a function of the angular $\vec{\vartheta}=\vec{\vartheta}_0+\Delta\vec{\vartheta}$ or linear coordinates $\vec{r}=\left(x',y'\right)\in D'$, where D' – receiving area of the OR.

To simplify the synthesis of the algorithm for estimating the parameters of a rough surface, we will assume that from the entire set of processes recorded by the elements of the matrix of an optical photosensitive device, independent temporal processes are analyzed, selected approximately at intervals equal to the correlation radius of the speckle pattern as a spatial random process. Such assumption was applied in the following works [20-22]. In this case, the positions of the receiving elements of the photosensitive device on its surface correspond to such angular $\vec{\vartheta}=\vec{\vartheta}_i=\vec{\vartheta}_0+i\delta\vec{\vartheta}$, or linear $\vec{r}'=\vec{r}_i'=i\Delta\vec{r}'$ coordinates.

Taking into account the above results the system of observation equations at the m-th wavelength and in the i-th receiving element will take the following form

$$\left\|u_{m,i}(t)\right\|=\left\|s_{m,i}\left(t,\vec{\zeta}\right)\right\|+\left\|n_{m,i}(t)\right\|, \qquad (14)$$

where indices $i=\overline{1,N}$ - numbers of receiving elements of the OR

$$s_{m,i}\left(t,\vec{\zeta}\right)=\operatorname{Re}\Big(e^{j\omega_m t}\int_D\dot{F}_m\left(\vec{r},\vec{\zeta}\right)\times$$
$$\times\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{r}_i',\vec{\vartheta}_0\right)\right]e^{-jk_m R\left(\vec{r},\vec{r}_i',\vec{\vartheta}_0\right)}d\vec{r}\Big), \quad (15)$$

where $s_{m,i}\left(t,\vec{\zeta}\right)$ is useful signals, which are independent time processes, corresponding to the spatial independent readings of the speckle image formed at the m-th wavelength, on the surface of the OR elements.

It can be assumed that on a small recording area of the light-sensitive device, the correlation function (12) does not depend on the coordinates $\vec{r}'$. Thus it is the same at the input of each i-th receiving element and expression (12) can be written in the following form,

$$R_{i\,s_m}\left(t_1,t_2,\vec{r}_i',\vec{\zeta}\right)=R_{s_m}\left(t_1,t_2,\vec{\zeta}\right)=$$
$$\sigma_m^0\left(\vec{q}_\perp,\vec{\zeta}\right)\Psi\left(t_1-t_2\right), \qquad (16)$$

$$\Psi\left(t_1-t_2\right)=\frac{1}{2}\operatorname{Re}\Big(e^{j\left\{\omega_m(t_1-t_2)\right\}}\Big)\times$$
$$\times\int_D\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]\dot{A}_m^*\left[t_2-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]d\vec{r}, \quad (17)$$

where

$$\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{\vartheta}_0\right)\right]\approx\dot{A}_m\left[t_1-t_d\left(\vec{r},\vec{r}_i',\vec{\vartheta}_0\right)\right].$$

Noise $n_{m,i}(t)$ are independent with the same correlation functions

$$n_{m,i}\left(t_1,t_2\right)=\left\langle n_{i\,m}\left(t_1\right)n_{i\,m}\left(t_2\right)\right\rangle=$$

$$= \left(N_{0i\,m}/2\right)\delta\left(t_1 - t_2\right),$$

$$N_{0i\,m} = N_{0m}. \qquad (18)$$

Due to the fact that the angular dimensions of the OR are small, we believe that the following is observed,

$$\sigma_m^0\left[\vec{q}_\perp\left(\vec{\vartheta}_i\right), \vec{\zeta}\right] \approx \sigma_m^0\left[\vec{q}_\perp\left(\vec{\vartheta}_0\right), \vec{\zeta}\right] =$$

$$= \sigma_m^0\left(\vec{\zeta}\right) = \sigma_m^0\left(\sigma_h, L_h\right). \qquad (19)$$

The effective scattering cross section is practically independent on small angular changes in coordinates within the surface of the OR.

Optimal algorithm synthesis

The algorithm for optimal estimation of the parameters of the studied SUS is synthesized by the method of finding the maximum of the likelihood functional. This conditional probability density functional for the case of registration of speckle patterns at several wavelengths (multispectral speckle pattern) will have the form

$$P\left[\vec{u}(t) \,|\, \vec{\zeta}\right] = \prod\nolimits_m^M \prod\nolimits_i^N P\left[u_{m,i}(t) \,|\, \vec{\zeta}\right]. \qquad (20)$$

Differentiating this functional with respect to the estimated parameters $\vec{\zeta}$, we come to the system of likelihood equations

$$\frac{\partial \ln\left(P\left[\vec{u}(t) \,|\, \vec{\zeta}\right]\right)}{\partial \zeta_\mu} = 0 = -\frac{1}{2}\sum\nolimits_m^M \sum\nolimits_i^N$$

$$\left\{ \begin{aligned} &\int_{T_m}\int_{T_m} \frac{\partial R_{u_{m,i}}\left(t_1, t_2, \vec{\zeta}\right)}{\partial \zeta_\mu} W_{u_{m,i}}\left(t_1, t_2, \vec{\zeta}\right) dt_1 dt_2 + \\ &+\int_{T_m}\int_{T_m} \frac{\partial W_{u_{m,i}}\left(t_1, t_2, \vec{\zeta}\right)}{\partial \zeta_\mu} u_{m,i}(t_1) u_{m,i}(t_2) dt_1 dt_2 \end{aligned} \right\}, \qquad (21)$$

where $W_{u_{m,i}}\left(t_1, t_2, \vec{\zeta}\right)$ is the function inverse to the correlation function that is calculated from the inversion equation of the form

$$\int\limits_{T_{m,i}} R_{m,i}\left(t_1, t_2, \vec{\zeta}\right) W_{u_{m,i}}\left(t_2, t_3, \vec{\zeta}\right) dt_2 = \delta\left(t_1 - t_3\right). \qquad (22)$$

Taking into account (16), we can assume that the correlation and inverse correlation functions do not depend on the index i, namely $R_{u_{m,i}} = R_{u_m}$, $W_{u_{m,i}} = W_{u_m}$. Equation (21) can be rewrite in the following form

$$\sum_{m=1}^{M}\left\{ N \int\limits_{T_m}\int\limits_{T_m} \frac{\partial R_{u_m}\left(t_1, t_2, \vec{\zeta}\right)}{\zeta_\mu} W_{u_m}\left(t_1, t_2, \vec{\zeta}\right) dt_1 dt_2 + \right.$$

$$\left. + \sum_{i=1}^{N} \int\limits_{T_m}\int\limits_{T_m} \frac{\partial W_{u_m}\left(t_1, t_2, \vec{\zeta}\right)}{\partial \zeta_\mu} u_{m,i}(t_1) u_{m,i}(t_2) dt_1 dt_2 \right\}. \qquad (23)$$

The correlation function $R_{u_m}\left(t_1, t_2\right)$ of the process $u_{m,i}(t)$ is stationary and depends on the difference of the arguments $t_1 - t_2$ and. It is based on (16), (18), (19) and has the form

$$R_{u_m}\left(t_1, t_2\right) = R_{s_m}\left(t_1, t_2, \vec{\zeta}\right) + R_{n_m}\left(t_1, t_2\right), \qquad (24)$$

where

$$R_{s_m}\left(t_1, t_2\right) = \sigma_m^0\left(\vec{\zeta}\right)\Psi_m\left(t_1 - t_2\right),$$

$$R_{n_m}\left(t_1, t_2\right) = \frac{N_{0m}}{2}\delta\left(t_1 - t_2\right).$$

Assuming that all random processes are statistically stationary it is expedient to find the solution of the likelihood equation (23) in spectral form by applying the direct Fourier transform. The Fourier transform of the correlation function (24) in accordance with the Khinchin-Wiener theorem is equal to the energy spectrum of the random process $u_{m,i}(t)$

$$G_{u_m}\left(f, \vec{\zeta}\right) = F\left[R_{u_m}\left(t_1 - t_2, \vec{\zeta}\right)\right] =$$

$$= \sigma_m^0\left(\vec{\zeta}\right) G_{\Psi m}(f) + \frac{N_{0m}}{2}, \qquad (25)$$

where

$$G_{\Psi m}(f) = F\left[\Psi_m\left(t_1 - t_2\right)\right]. \qquad (26)$$

We assume that the width of this correlation function is significantly less than the observation time interval T_m. This allows to pass to infinite limits in the inversion equation (22) and write it in the form of the convolution integral

$$\int\limits_{-\infty}^{\infty} R_m\left(t - \tau, \vec{\zeta}\right) W_{u_m}\left(\tau, \vec{\zeta}\right) d\tau = \delta(t).$$

Applying the direct Fourier transform to this equation we find the spectrum of the inverse correlation function

$$F\left[W_{u_m}\left(t_1 - t_2, \vec{\zeta}\right)\right] = 1\big/ G_{u_m}\left(f, \vec{\zeta}\right) =$$

$$= 1\Big/ \sigma_m^0\left(\vec{\zeta}\right) G_{\Psi m}(f) + \frac{N_{0m}}{2}, \qquad (27)$$

which is the reciprocal of the energy spectrum of the random process $u_{m,i}(t)$.

Then the likelihood equation (23) in the spectral region will have the following form

$$\sum\nolimits_{m=1}^{M}\left\{ N T_m \int_{-\infty}^{\infty} \frac{\partial}{\partial \zeta_\mu}\left[\ln G_{u_m}\left(f, \vec{\zeta}\right)\right] df - \right.$$

$$- \sum\nolimits_{i=1}^{N} \int_{-\infty}^{\infty} \frac{\partial}{\partial \zeta_\mu}\left[\ln G_{u_m}\left(f, \vec{\zeta}\right)\right] \times$$

$$\left. \times G_{u_m}^{-1}\left(f, \vec{\zeta}\right) \left|\dot{S}_{T_{m,i}}\left(j 2\pi f\right)\right|^2 df \right\} = 0, \qquad (28)$$

where

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$$\dot{S}_{T_{m,i}}(j2\pi f)=\int_{T_{m,i}} u_{m,i}(t)e^{-j2\pi ft}\,dt. \qquad (29)$$

Equation (28) can be represented as

$$\sum_{m=1}^{M}\frac{\partial\sigma^0(\lambda_m,\vec{\zeta})}{\partial\zeta_\mu}\left\{N\int_{-\infty}^{\infty}\frac{G_{\Psi_m}(f)}{\sigma^0(\lambda_m,\vec{\zeta})G_{\Psi_m}(f)+\frac{N_{0m}}{2}}df-\right.$$

$$-\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{G_{\Psi_m}(f)}{\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\Psi_m}(f)+\frac{N_{0m}}{2}\right]^2}\times$$

$$\left.\times\frac{\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2}{T}df\right\}=0 \qquad (30)$$

or in vector-matrix form

$$\underline{\sigma}^{0\prime}\vec{X}=\left\|\sum_{m=1}^{M}\sigma^{0\prime}_{m\mu}X_m\right\|=0. \qquad (31)$$

Since the matrix

$$\underline{\sigma}^{0\prime}=\left\|\sigma^{0\prime}_{m\mu}\right\|=\left\|\frac{\partial\sigma^0(\lambda_m,\vec{\zeta})}{\partial\zeta_\mu}\right\|, \qquad (32)$$

is generally nonzero, then

$$\vec{X}=\left\|X_m\right\|=\left\|N\int_{-\infty}^{\infty}\frac{G_{\psi_m}(f)}{\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0m}}{2}}df-\right.$$

$$-\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{G_{\psi_m}(f)}{\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0m}}{2}\right]^2}\times$$

$$\left.\times\frac{\left|\dot{S}_{m,i}(j2\pi f)\right|^2}{T}df\right\|=0. \qquad (33)$$

Multiplying the numerator and denominator in the left term by the same denominator we rewrite system (33) in the form

$$N\int_{-\infty}^{\infty}\frac{G_{\psi_m}(f)\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0m}}{2}\right]}{\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0m}}{2}\right]^2}df=$$

$$=\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{G_{\psi}(f)}{\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi}(f)+\frac{N_{0m}}{2}\right]^2}\times$$

$$\times\frac{\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2}{T}df. \qquad (34)$$

Average value of the periodogram $\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2$ in equation (34) has the following form

$$\lim_{T\to\pm\infty}\left\langle\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2\right\rangle=\lim_{T\to\infty}\int_{-T/2}^{T/2}\int_{-\infty}^{\infty}\left\langle u_{m,i}(t_1)u_{m,i}(t_2)\right\rangle\times$$

$$\times e^{j2\pi f(t_1-t_2)}dt_1dt_2=\lim_{T\to\infty}T\int_{-\infty}^{\infty}R_{u_m}(\tau)e^{j2\pi f}d\tau=$$

$$=\lim_{T\to\infty}TG_{u_m}(f,\vec{\zeta}). \qquad (35)$$

To solve this system, i.e. to find the optimal estimates of the required parameters of the SUS, it is necessary to form a periodogram $\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2$ at each of the frequencies of the probing signal in the corresponding receiving channel $u_{m,i}(t)$, perform weight integration over frequencies and then equate result to the left side of the equation, which should contain the known dependences on the sought parameters $\vec{\zeta}$.

We rewrite the right-hand side of equation (34) in the following form

$$\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{G_{\psi_m}(f)}{\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0m}}{2}\right]^2}\times$$

$$\times\frac{\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2}{T}df=\sum_{i=1}^{N}\int_{-\infty}^{\infty}\left|\dot{K}_{\text{dek filt}}(j2\pi f)\right|^2\times$$

$$\times\frac{\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2}{T}df=\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{\left|\dot{S}_{\text{dek }T_{m,i}}(j2\pi f)\right|^2}{T}df, \qquad (36)$$

and the left - in this one

$$N\int_{-\infty}^{\infty}\left|\dot{K}_{\text{dek filt}}(j2\pi f)\right|^2\times$$

$$\times\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+0{,}5N_{0k}\right]df. \qquad (37)$$

Then the system of equations (34) takes the form

$$N\int_{-\infty}^{\infty}\left|\dot{K}_{\text{dek filt}}(j2\pi f)\right|^2\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+\frac{N_{0k}}{2}\right]df=$$

$$=\sum_{i=1}^{N}\int_{-\infty}^{\infty}\left|\dot{K}_{\text{dek filt}}(j2\pi f)\right|^2\frac{1}{T}\left|\dot{S}_{T_{m,i}}(j2\pi f)\right|^2df, \qquad (38)$$

where

$$\left|\dot{K}_{\text{dek filt}}(j2\pi f)\right|^2=\left|\dot{K}_{\text{dek filt}}(j2\pi f)\dot{K}^*_{\text{dek filt}}(j2\pi f)\right|=$$

$$=G_{\psi_m}(f)\left[\sigma^0(\lambda_m,\vec{\zeta})G_{\psi_m}(f)+0{,}5N_{0k}\right]^{-2}. \qquad (39)$$

In expression (39) $\dot{K}_{\text{dek filt}}(j2\pi f)$ is the transfer characteristic of the filter that decorrelates (denominator) and filters (numerator) of the received oscillations in time.

Using the Parseval-Laplace theorem, we write the right-hand side of Eq. (38) in the following form

$$\sum_{i=1}^{N}\int_{-\infty}^{\infty}\frac{1}{T_m}\left|\dot{S}_{dek\,T_{m,i}}(j2\pi f)\right|^2 df \approx$$

$$\approx \sum\nolimits_{i=1}^{N}\frac{1}{T_m}\int_0^T u^2{}_{dek\,m,i}(t) =$$

$$= \sum_{i=1}^{N} P_{mean,dek,m,i} = P_{mean,dek,m},$$

where $P_{mean,dek,m,i}$ is an estimate of the average power of the received signal at the output of the i-th element of the matrix receiver at the m-th wavelength of the probing signal, and $P_{mean,dek,m}$ is the total estimate of the average power of all the received signals corresponding to independent counts of the speckle pattern in the m-th wavelength.

Finally, we bring expression (38) to the form

$$\sigma^0\left(\lambda_m,\vec{\zeta}\right) = \frac{P_{mean,dek,m}}{P_{\psi_m}}, \qquad (40)$$

where $P_{\psi_m} = N\int_{-\infty}^{\infty} G_{\psi_m}(f)df$.

The block diagram of the optimal meter for the effective scattering cross section of SUS by multi-element OR at the m-th number of wavelengths is shown in Fig. 2.

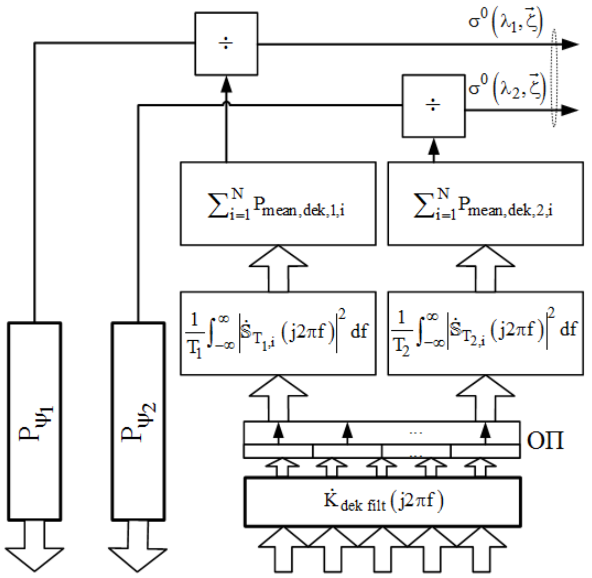

Fig. 2. Block diagram of the optimal effective scattering cross section estimation of a statistically uneven surface at two wavelengths

Calculation of the limiting errors in the estimation of the measured parameters

Limit errors of parameter estimation $\vec{\zeta}$ are determined by the diagonal elements of the matrix inverse to the Fisher information matrix. The main diagonal of the Fisher information matrix has information about the limiting variances of errors corresponding to the boundary below which the root mean square (RMS) values cannot be obtained.

Fisher matrix has the following form

$$\Phi_{\mu\nu} = \left\langle \frac{\partial^2 \ln\left(P\left[\vec{u}(t)/\vec{\zeta}\right]\right)}{\partial\zeta_\mu \zeta\lambda_\nu} \right\rangle\Bigg|_{\vec{\zeta}=\hat{\vec{\zeta}}} = -\frac{1}{2}N\sum_{m=1}^{M}\left\{\int_0^T \times\right.$$

$$\left.\times\int_0^T \frac{\partial W_{u_m}\left(t_1-t_2,\vec{\zeta}\right)}{\partial\zeta_\mu}\frac{\partial R_{u_m}\left(t_1-t_2,\vec{\zeta}\right)}{\partial\zeta_\nu}dt_1dt_2\right\}\Bigg|_{\vec{\zeta}=\hat{\vec{\zeta}}}. \qquad (41)$$

Expressing through the spectra $G_{k\Sigma}$ and G_k correlation R_{u_k} and inverse correlation W_{u_k} function and taking into account (25, 27) Fisher matrix takes form:

$$\Phi_{\mu\nu} = -\frac{1}{2}N\sum_{m=1}^{M}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\partial}{\partial\zeta_\mu}\left[\frac{1}{G_{u_m}\left(f_1,\vec{\zeta}\right)}\right]\times$$

$$\times\frac{\partial}{\partial\zeta_\nu}\left[G_{u_m}\left(f_2,\vec{\zeta}\right)\right]e^{j2\pi f_1(t_1-t_2)}e^{j2\pi f_2(t_1-t_2)}df_1df_2dt_1dt_2 =$$

$$= \frac{1}{2}N\sum_{m=1}^{M}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\dfrac{\partial G_{u_m}\left(f_1,\vec{\zeta}\right)}{\partial\zeta_\mu}\dfrac{\partial G_{u_m}\left(f_2,\vec{\zeta}\right)}{\partial\zeta_\nu}}{G^2_{u_m}\left(f_1,\vec{\zeta}\right)}\times$$

$$\times\int_0^{T_m}\int_0^{T_m} e^{j2\pi(f_1+f_2)(t_1-t_2)}df_1df_2dt_1dt_2 \approx$$

$$\approx N\sum_{m=1}^{M}T_m\int_{-\infty}^{\infty}\frac{\partial\ln G_{u_m}\left(f,\vec{\zeta}\right)}{\partial\zeta_\mu}\frac{\partial\ln G_{u_m}\left(f,\vec{\zeta}\right)}{\partial\zeta_\nu}df =$$

$$= \frac{N}{2}\sum_{m=1}^{M}T_m\int_{-\infty}^{\infty}\frac{G^2_{A_m}(f)\left[\dfrac{\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\mu}\right]\left[\dfrac{\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\nu}\right]}{\left[\sigma^0\left(\lambda_m,\vec{\zeta}\right)G_{A_m}(f)+\dfrac{N_{0m}}{2}\right]^2}df. \qquad (42)$$

Finally

$$\Phi_{\mu\nu} = \frac{N}{2}\sum_{m=1}^{M}T_m\Delta f_m\left(\vec{\zeta}\right)\frac{\partial\ln\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\mu}\frac{\partial\ln\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\nu}, \qquad (43)$$

where

$$\Delta f_m = \int_{-\infty}^{\infty}\frac{G^2_{A_m}(f)}{\left[G_{A_m}(f)+\dfrac{N_{0m}}{2\sigma^0\left(\vec{\vartheta}_m,\vec{\zeta}\right)}\right]^2}df \qquad (44)$$

is the bandwidth of the energy spectrum of the useful signal at the output of the optimal filter. The square of the frequency response of the optimal filter

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$\left|\dot{K}_{\text{dek filt}}\left(j2\pi f\right)\right|^2$ is given by expression (39). It performs operations of decorrelation and matched filtering of the input signal. At the input of this filter the shape of the energy spectrum of the useful signal is determined by the function $G_{\Psi m}\left(f\right)$.

Formula (44) can be expressed in the detail view

$$\Delta f_m = \int_{-\infty}^{\infty} \frac{G_{A_m}^2\left(f\right)\left[2\sigma^0\left(\lambda_m,\vec{\zeta}\right)/N_{0m}\right]^2}{\left[G_{A_m}\left(f\right)\left[2\sigma^0\left(\lambda_m,\vec{\zeta}\right)/N_{0m}\right]+1\right]^2} df = \int_{-\infty}^{\infty}\frac{\left[2\mu\left(f\right)\right]^2}{\left[2\mu\left(f\right)+1\right]^2}df,$$

where

$$\mu\left(f\right)=\frac{G_{A_m}\left(f\right)\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{N_{0m}} \qquad (45)$$

is the signal-to-noise power ratio depending on frequency f (quantity σ^0 is dimensionless). Increasing $\mu\left(f\right)$ leads to widening bandwidth Δf_m of the optimal filter. At the same time measurement errors are reducing. In the case of $\mu\left(f\right)\to\infty$ the integrand tends to unity, and $\Delta f_m\to\infty$. In this case, the errors in the estimates of the parameters $\vec{\zeta}$ tend to zero.

If the frequency bands $\Delta f_m\left(\vec{\zeta}\right)=\Delta f$ are independent on parameters $\vec{\zeta}$ and are the same for any λ_m then the observation times is the same $T_m = T$. Taking this statement into account formula (43) takes the form

$$\Phi_{\mu\nu}=\frac{NT\Delta f}{2}\sum_{m=1}^{M}\frac{\partial\ln\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\mu}\frac{\partial\ln\partial\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_\nu}. \qquad (46)$$

It is of interest to consider the case of estimating only two unknown parameters (M = 2) when observed signals are received at two different frequencies. In this case, the Fisher matrix has the form,

$$\Phi=\frac{NT\Delta f}{2}\times \qquad (47)$$

$$\times\begin{Vmatrix}\sum_{m=1}^{2}\left(\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_1}\right)^2 & \sum_{m=1}^{2}\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_1}\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_2} \\ \sum_{m=1}^{2}\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_1}\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_2} & \sum_{m=1}^{2}\left(\frac{\partial\ln\sigma^0\left(\lambda_m,\vec{\zeta}\right)}{\partial\zeta_2}\right)^2\end{Vmatrix}.$$

Limiting variances of parameter measurement errors λ_1, λ_2, are obtained from the matrix inverse to (47)

$$\sigma_{\zeta_{1(2)}}^2=\frac{2}{NT\Delta f}\times$$

$$\times\frac{\left(\frac{\partial\ln\sigma^0\left(\lambda_1,\vec{\zeta}\right)}{\partial\zeta_{2(1)}}\right)^2+\left(\frac{\partial\ln\sigma^0\left(\lambda_2,\vec{\zeta}\right)}{\partial\zeta_{2(1)}}\right)^2}{D_{denom}}, \qquad (48)$$

where D_{denom} – determinant of matrix (47)

$$D_{denom}=\left(\frac{\partial\ln\sigma^0\left(\lambda_2,\vec{\zeta}\right)}{\partial\zeta_1}\frac{\partial\ln\sigma^0\left(\lambda_1,\vec{\zeta}\right)}{\partial\zeta_2}-\frac{\partial\ln\sigma^0\left(\lambda_1,\vec{\zeta}\right)}{\partial\zeta_1}\frac{\partial\ln\sigma^0\left(\lambda_2,\vec{\zeta}\right)}{\partial\zeta_2}\right)^2.$$

Optimal estimation of the parameters of a small-scale statistically uneven surface

Small-scale statistically uneven surface satisfies the conditions $h\left(\vec{r}\right)<<\lambda$, $\left|\nabla_\perp h\left(\vec{r}\right)\right|<<1$, $\vec{r}=\left(x,y\right)$, where h is the height of the irregularities; $\nabla_\perp=\left(\frac{\partial}{\partial x},\frac{\partial}{\partial y}\right)$ is transverse differentiation operator (gradient).

The effective scattering cross section of a small-scale surface has the following form

$$\sigma_n^0=4k^4\pi^{-1}\left|\dot{M}_n\right|^2\cos^2\theta_i\cos^2\theta_s W\left(\vec{q}_\perp\right), \qquad (49)$$

where $W\left(\vec{q}_\perp\right)$ is energy spectrum;

$\dot{M}_n$ is the coefficient that depends on angles θ_i, θ_s and dielectric constant ε.

Energy spectrum of irregularities has the following form

$$W\left(\vec{q}_\perp\right)=\pi\sigma_h^2L_h^2 e^{-\beta^2\left(\sin^2\theta_i+\sin^2\theta_s-2\sin\theta_i\sin\theta_s\cos\phi_s\right)}, \qquad (50)$$

where $\beta=0.5kL_h$.

Taking into account (50) the equation (49) has the form

$$\sigma_n^0=4k^4\left|\dot{M}_n\right|^2 b\sigma_h^2L_h^2e^{-\beta^2 a}, \qquad (51)$$

where

$$a=\sin^2\theta_i+\sin^2\theta_s-2\sin\theta_i\sin\theta_s\cos\phi_s,$$
$$b=\cos^2\theta_i\cos^2\theta_s.$$

Equation (51) for recording reflected oscillations for two wavelengths gives the following results

$$\sigma_n^0=4k^4\left|\dot{M}_n\right|^2 b\sigma_h^2L_h^2e^{-\beta^2 a}, \qquad (52)$$

$$\sigma_2^0=4k_2^4\left|\dot{M}\right|^2 b\sigma_h^2L_h^2e^{-\beta_2^2 a}, \qquad (53)$$

where $k_{1(2)}=2\pi/\lambda_{1(2)}$, $\beta_{1(2)}=0.5k_{1(2)}L_h$.

Dividing (52) by (53) gives the next results

$$\frac{\sigma_1^0}{\sigma_2^0}=\frac{P_{cp.}\left(\lambda_1\right)}{P_{cp.}\left(\lambda_2\right)}=\frac{k_1^4e^{-\beta_1^2a}}{k_2^4e^{-\beta_2^2a}}=\left|\frac{k_1^4}{k_2^4}=K_{\lambda\lambda}\right|,$$

$$\frac{e^{-\beta_1^2 a}}{e^{-\beta_2^2 a}} = \frac{1}{K_{\lambda\lambda}} \frac{P_{cp.}(\lambda_1)}{P_{cp.}(\lambda_2)}, \qquad (54)$$

then

$$L_h^2 \left(\left(\frac{\pi}{\lambda_1} \right)^2 - \left(\frac{\pi}{\lambda_2} \right)^2 \right) = -\frac{\ln\left(\frac{1}{K_{\lambda\lambda}} \frac{P_{cp.}(\lambda_1)}{P_{cp.}(\lambda_2)} \right)}{a}. \qquad (55)$$

Correlation radius L_h and root mean square height of irregularities σ_h can be found as follows

$$\zeta_1 = L_h = \sqrt{ -\frac{\ln\left(\frac{1}{K_{\lambda\lambda}} \frac{P_{cp.}(\lambda_1)}{P_{cp.}(\lambda_2)} \right)}{a\left(\left(\frac{\pi}{\lambda_1} \right)^2 - \left(\frac{\pi}{\lambda_2} \right)^2 \right)} }, \qquad (56)$$

$$\zeta_2 = \sigma_h = \sqrt{ \frac{P_{cp.}(\lambda_1)}{P_{A,\lambda_1}} \frac{1}{4k_1^4 \left|\dot{M}\right|^2 b L_h^2 e^{-\beta_1^2 a}} }. \qquad (57)$$

Investigation of the ranges of viewing angles and calculation of the limiting errors of measurements of the parameters of small-scale SUS

In the process of setting up experiments or constructing a measuring system, an important element is the choice of the optimal characteristics of its components, as well as the geometric parameters of their installation. For this, the matrices inverse to the Fisher information matrices is studied. The diagonal elements of this matrix depend on the features of the nonlinear connection of the complex amplitudes of the received optical oscillations with the estimated parameters and are determined by electrodynamic models. This makes it possible to investigate the lower bounds of the variances of the estimates of the measured parameters. These estimates correspond to the ultimate measurement accuracy. A detailed analysis of these errors allows us to choose the optimal measurement conditions.

According to the synthesized algorithm for optimal estimation of the effective scattering cross-section of statistically uneven surfaces (40) and the structural diagram built on its basis (Fig. 2) an optical scheme for measuring the parameters of statistically uneven surfaces was developed (Fig. 3). In the scheme: 1, 2 are lasers with different wavelengths; 3 is an investigated statistically uneven surface; 4 is the multi-element optical receiver. To find the optimal angles of installation of lasers and a multielement optical receiver, as well as to select radiation sources that provide the required accuracy in measuring wavelengths, according to formulas (48) and (49), the limiting errors of the estimated parameters of statistically uneven surfaces are calculated using an electrodynamic model of a small-scale surface.

The initial conditions for the study of the accuracy characteristics of the synthesized optimal algorithm for estimating the parameters of statistically uneven surfaces were specified as follows: wavelengths of emitters $\lambda_1 = 650\ \text{nm}$ and $\lambda_1 = 405\ \text{nm}$, RMS height of irregularities $\sigma_h = 0.01\ \text{mkm}$, Roughness correlation radius $L_h = 0.1\ \text{mkm}$.

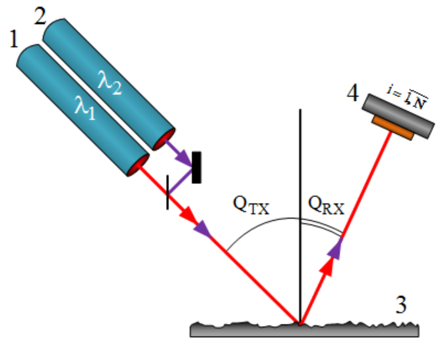

Fig. 3. Optical scheme for estimating the parameters of statistical uneven surfaces

Graphs of the dependences of the limiting values of the variances of the estimates of two parameters, the root-mean-square height of the irregularities σ_h and the correlation radius of irregularities L_h corresponding to all possible combinations of the angular positions of the emitters and the multi-element optical receiver in the range of angles from 0° up to 90° with a step in 0.1°, are shown in Fig. 4 and Fig. 5. Along the abscissa axis the angular positions of the OR Q_{RX} are plotted. The ordinate is the angular position of the emitters Q_{TX}.

By enumerating the angular positions of the emitters and the receiver with a simultaneous search for the minimum error in the joint determination of the group of the sought parameters, as well as taking into account the real conditions of the experiment, the optimal angles of the lasers were chosen $Q_{TX} = 0.1^\circ(60^\circ)$ and positions of the multi-element optical receiver $Q_{RX} = 60^\circ(0.1^\circ)$.

Namely, for a given surface illumination angle Q_{TX} and the installation angle of the multi-element optical receiver Q_{RX} the absolute errors in determining the root-mean-square height of irregularities were calculated $5.1275 \cdot 10^{-8}\ \text{mkm}$ and correlation radius $2.0212 \cdot 10^{-3}\ \text{mkm}$.

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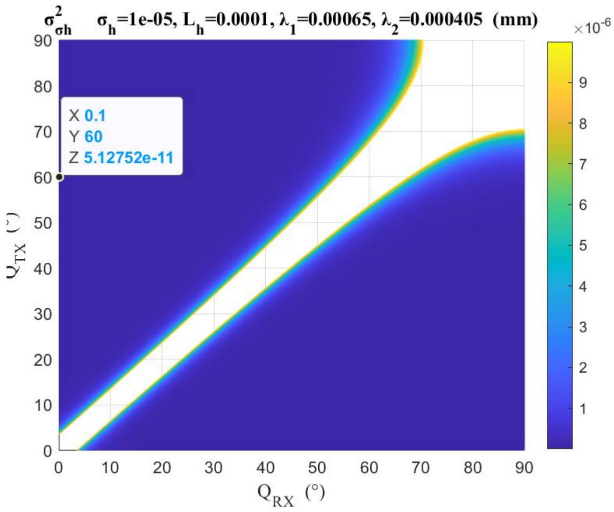

Fig. 4. Dependence of the maximum measurement errors of the standard deviation of the height of irregularities σ_h SUS from installation angles transmitters and receiver

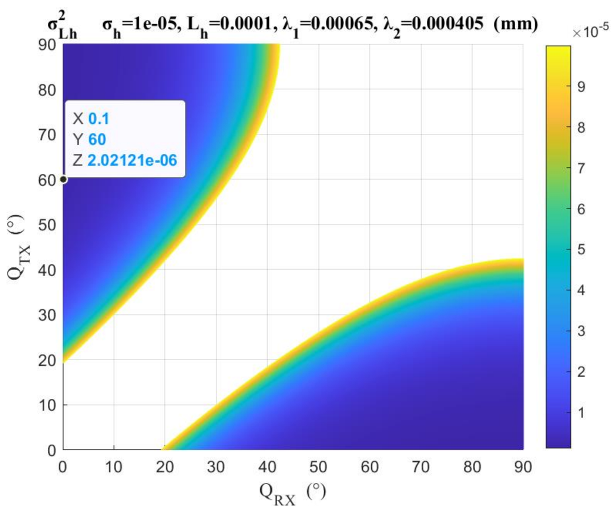

Fig. 5. Dependence of the maximum measurement errors of the standard deviation of the correlation radius of irregularities L_h SUS from installation angles emitters and receiver

Conclusions

The problem of optimal estimation of the parameters and statistical characteristics of the investigated statistically uneven surface by a multielement optical receiver is solved. The algorithm for optimal processing of optical signals has been synthesized, and a corresponding block diagram has been developed.

The diagonal elements of the covariance matrix inverse to the Fisher information matrix were analyzed. As a result the limiting errors of the estimated parameters of statistically uneven surfaces were investigated and the recommended installation angles of the emitters and optical receiver were determined.

Equations for estimating the root-mean-square height of irregularities and the correlation radius of a small-scale statistically irregular surface are obtained in the approximation of small perturbations.

The developed method for estimating the parameters of SUS will allow:

1) increase the accuracy of measurements;

2) conduct a non-contact assessment of the parameters of the SUS;

3) to measure the parameters of statistically uneven surfaces that have geometric surface heterogeneity or are located in hard-to-reach places, for example grooves, holes, as well as products of cylindrical, spherical, and other shapes.

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СИНТЕЗ ОПТИМАЛЬНОГО АЛГОРИТМУ ТА СТРУКТУРИ БЕЗКОНТАКТНОГО ОПТИЧНОГО ПРИСТРОЮ ДЛЯ ОЦІНКИ ПАРАМЕТРІВ СТАТИСТИЧНО НЕРІВНИХ ПОВЕРХОНЬ

О. Шматко, В. Волосюк, С. Жила, В. Павликів, М. Руженцев, Е. Церне, А. Попов, І. Остроумов, Н. Кузьменко, К. Дергачов, О. Сущенко, Ю. Авер'янова, М. Заліський, О. Соломенцев, О. Гавриленко, Б. Кузнецов, Т. Нікітіна

Виробництво деталей та (або) готових виробів в радіоелектроніці, машинобудуванні та інших галузях промисловості нерозривно пов'язане з контролем точності і чистоти оброблюваних поверхонь. Існуючі на сьогоднішній день вимірювачі параметрів статистично нерівних поверхонь, як контактні, так і безконтактні мають ряд недоліків, а також обмеження, обумовлених методами і конструктивними особливостями вимірювань. Спекл-інтерферометричні методи вимірювань параметрів статистично нерівних поверхонь дають можливість позбавитись від ряду недоліків, притаманних існуючим методам і засобам вимірювань. Використання методів статистичної радіотехніки, а саме, методів оптимізації статистичних рішень і оцінок параметрів ймовірнісних розподілів для синтезу оптимальних радіотехнічних систем є перспективним і для синтезу оптико-електронних когерентних лазерних систем просторово-часової обробки сигналів (спекл-зображень), сформованих розсіяним статистично нерівними поверхнями лазерним випромінюванням. Мета даної роботи синтез оптимального алгоритму та структури безконтактного оптичного пристрою для аналізу параметрів статистично нерівних поверхонь на основі просторово-часової обробки оптичних спекл-інтерференційних сигналів і зображень з використанням сучасних методів оптимального синтезу радіотехнічних і когерентних оптико-електронних систем. У даній роботі синтезований і вивчений алгоритм обробки оптичних сигналів, розсіяних статистично нерівними поверхнями, для задач оптимального оцінювання параметрів і характеристик статистично нерівних поверхонь. Запропоновано структурну схему оптичного безконтактного пристрою для оцінки параметрів статистично нерівних поверхонь. Досліджено граничні похибки розрахункових параметрів статистично нерівних поверхонь і оптимальні кути установки випромінювачів і оптичного приймача. Отримано рівняння для оцінки середньо-квадратичної висоти і радіуса кореляції дрібномасштабних статистично нерівних поверхонь в наближенні малих збурень. Запропонований метод оцінки параметрів статистично нерівних поверхонь дозволяє підвищити точність вимірювань, провести безконтактну оцінку параметрів статистично нерівних поверхонь, що мають геометричні неоднорідності поверхні або розташованих у важкодоступних місцях, наприклад, пази, отвори, а також вироби циліндричної, сферичної та інших форм.

Ключові слова: шорсткість поверхні; лазер; спекл-зображення; оптимальний алгоритм; оптичний приймач; статистично нерівна поверхня.

СИНТЕЗ ОПТИМАЛЬНОГО АЛГОРИТМА И СТРУКТУРЫ БЕСКОНТАКТНОГО ОПТИЧЕСКОГО ПРИБОРА ДЛЯ ОЦЕНИВАНИЯ ПАРАМЕТРОВ СТАТИСТИЧЕСКИ НЕРОВНЫХ ПОВЕРХНОСТЕЙ

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Производство деталей и(или) готовых изделий в радиоэлектронике, машиностроении и других отраслях промышленности неразрывно связано с контролем точности и чистоты обрабатываемых поверхностей. Существующие на сегодняшний день измерители параметров статистически неровных поверхностей, как контактные, так и бесконтактные имеют ряд недостатков, а также ограничений, обусловленных методами и конструктивными особенностями средств измерения. Спекл-интерферометрические методы измерений параметров статистически неровных поверхностей дают возможность уйти от ряда недостатков, присущих существующим методам и средствам измерений. Использование методов статистической радиотехники, а именно, методов оптимизации статистических решений и оценок параметров вероятностных распределений для синтеза оптимальных радиотехнических систем является перспективным и для синтеза оптико-электронных когерентных лазерных систем пространственно-временной обработки сигналов (спекл-изображений), сформированных рассеянным статистически неровными поверхностями лазерным излучением. Цель данной работы синтез оптимального алгоритма и структуры бесконтактного оптического прибора для оценивания параметров статистически неровных поверхностей на основе пространственно-временной обработки оптических спекл-интерференционных сигналов и изображений с использованием современных методов оптимального синтеза радиотехнических и когерентных оптико-электронных систем. В данной работе синтезирован и исследован оптимальный алгоритм обработки оптических сигналов, рассеянных статистически неровными поверхностями, для задач оптимального оценивания параметров и статистических характеристик статистически неровных поверхностей. Предложена структурная схема оптического бесконтактного устройства для оценки параметров статистически неровных поверхностей. Исследованы предельные погрешности расчетных параметров статистически неровных поверхностей и определены оптимальные углы установки излучателей и оптического приемника. Получены уравнения для оценки среднеквадратической высоты неровностей и радиуса корреляции мелкомасштабных статистически неровных поверхностей в приближении малых возмущений. Предлагаемый метод оценки параметров статистически-неровных поверхностей позволяет повысить точность измерений, провести бесконтактную оценку параметров статистически неровных поверхностей, измерить параметры статистически неровных поверхностей, имеющих геометрические неоднородности поверхности или расположенные в труднодоступных местах, например, пазы, отверстия, а также изделий цилиндрической, сферической и других форм.

Ключевые слова: шероховатость поверхности; лазер; спекл-картина; оптимальный алгоритм; оптический приемник; статистически неровная поверхность.

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