ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 629.7.052.3:621.396.676-027.236

doi: 10.32620/reks.2021.1.04

**V. VOLOSYUK, S. ZHYLA, V. PAVLIKOV, D. VLASENKO,
V. KOSHARSKYI, D. KOLESNIKOV, O. INKARBAIEVA, K. NEZHALSKAYA**

National Aerospace University "Kharkiv Aviation Institute", Ukraine

OPTIMAL RADAR CROSS SECTION ESTIMATION IN SYNTHETIC APERTURE RADAR WITH PLANAR ANTENNA ARRAY

The optimization problem of statistical synthesis of the method for radar cross section estimation in synthetic aperture radar with planar antenna array is solved. The desired radar cross section is given as a statistical characteristic of a spatially inhomogeneous complex scattering coefficient of the studying media. In fact it is developed new methods of inverse problems solution not with respect to the restoration of coherent images in the form of spatial distribution of complex scattering coefficient but with respect to the statistical characteristics of inhomogeneous (spatially nonstationary) random processes. The electrophysical parameters of surfaces and their statistical characteristics are considered as functions of spatial coordinates. The maximum likelihood method was chosen as the optimization method. The obtained results make it possible to determine the multichannel structure, the optimal method of surface observation and the potential spatial resolution in aerospace scatterometric radars with antenna array. Optimal operations for processing space-time signals are determined and a modified method for synthesizing antenna aperture is proposed, which in contrast to the classical algorithm for synthesizing antenna aperture that integrates the product of the received signal and the reference signal equal to a single signal additionally implements the decorrelation of signals reflected from the earth's surface, The new operation of the scattered signals decorrelation consists in their integration with the space-time inverse correlation function. To confirm the reliability of the results obtained, simulation modeling of the classical method for the synthesis of coherent images and the proposed optimal one was carried out. From the analysis of the results it flows that propose method has higher quality and smaller size of spackle noise. The results obtained in the article can be used to develop and substantiate the requirements for the tactical and technical characteristics of promising aerospace-based scatterometric radars with planar phased antenna arrays.

Keywords: *synthetic aperture radar; radar cross section; statistical optimization*.

Introduction

Modern studies of the Earth's surface cannot be performed without information obtained by remote sensing systems installed on various aero-space platforms. Recently a large number of satellites with scientific equipment on board has been launched all over the world. A huge amount of information received from the satellite is used not only for scientific purposes, but also for solving many economic, environmental and military tasks. The standard methods of remote sensing of the Earth's surface, seas and oceans using the optical range are ineffective at night, in bad weather conditions and for estimation the electrophysical parameters of various natural environments. Only when high spatial resolution airborne synthetic aperture radars (SAR) had been developed new important and interesting results were obtained in the hydrodynamics of the water surface, topography, agriculture, glaciology for the first time. Thus all resurches devoted to the optimization of the structure of onboard radar systems are relevant and require further development.

In recent years the great attention has been paid to the technical implementation of aerospace radars [1-3] based on a new element base and the analysis of digital radar images of the underlying surface of the Earth. At the same time, a further increase in the accuracy and global scope of radio vision is possible only as a result of end-to-end optimization of the spatiotemporal processing of received electromagnetic fields.

Usually synthetic aperture radar is designed to estimate complex scattering coefficient as an unknown parameter in a functionally determined model of received spatio-temporal signals. The result in this case will be distorted by multiplicative noise, speckles, which make it difficult to determine the concept of the image itself. Further improvement of the radar image is carried out by smoothing the primary estimates of the complex scattering coefficient or their square module by various filters. As a result, the obtained images are close to the estimation of the radar cross section (RCS). Such RCS estimates are not optimal, since they were obtained heuristically without optimization problem solving.

Statistical synthesis of the optimal method of RCS estimation as a statistical characteristic of the complex scattering coefficient and optimization of the imaging technique in radar scatterometer is the goal of this article. Generalized problem of spatio-temporal signal processing in aerospace radio engineering system with moving planar antenna arrays is reasonably to solve using modern advances in statistical theory of remote sensing radio engineering systems [4-10]. In particular, it is necessary to use the results of basics of statistical synthesis of radio systems [4], modern algorithms for high resolution imaging [5], results of the statistical synthesis of optimal and quasi-optimal passive radars [6] and quasioptimal spatiotemporal signal processing algorithms for radar imaging [7] in a complex.

Geometry of the surface measurements and model of the received signal

We will consider on Fig. 1 geometry of surface sensing from an aircraft located at a height H and moving in a plane $y=0$ at a constant speed V parallel to the axis x. Parameters H and V are known. Suppose that on board, parallel to the plane Oxy, there is the registration area with coordinates $\vec{r}'=(x', y', z')\in D'$. According to the given geometry, the coordinates of the phase center of the region D' are $(x'=Vt,\ y'=0,\ z'=H)$ at an arbitrary instant of time t.

Using a small area around the phase center of the registration plane or one antenna array element, in the case of discrete idealization, in the direction of the surface D under study, in a wide sector of angles, a signal $s_t(t)$ is transmitted,

$$s_t(t)=A(t)\cos(2\pi f_0 t+\phi)=\mathrm{Re}\{\dot{A}(t)e^{j\omega_0 t}\}, \qquad (1)$$

where $A(t)$ is the envelope of the probe signal, $\dot{A}(t)=A(t)e^{j\phi}$ is the complex envelope that takes into account some initial phase ϕ, f_0 is the center frequency, $\omega_0=2\pi f_0$ is the circular frequency.

The transmitted signal reaches the surface D with coordinates $\vec{r}=(x, y, 0)\in D$, reflects from it and is received by each antenna element with coordinates $\vec{r}'=(x', y', H)\in D'$ and a complex amplitude-phase distribution $\dot{I}(\vec{r}')$.

The signals received by the registration area are stochastic and have the following form [11, 12]:

$$\dot{s}(t,\vec{r}')=\int_D \dot{F}(\vec{r})\dot{s}_0(t,\vec{r},\vec{r}')d\vec{r}, \qquad (2)$$

where $\dot{F}(\vec{r})$ is the specific complex scattering coefficient of some fairly small area element $d\vec{r}$, $\dot{F}(\vec{r})$ is spatially inhomogeneous stochastic process,

$$\dot{s}_0(t,\vec{r},\vec{r}')=\varepsilon\dot{I}(\vec{r}')\dot{A}(t-t_d(\vec{r},\vec{r}'))\times$$
$$\times\exp[j2\pi f_0(t-t_d(\vec{r},\vec{r}'))], \qquad (3)$$

is the unit signal reflected from a surface element $d\vec{r}$ having $\dot{F}(\vec{r})=1$, ε is the attenuation of the signal on the propagation path, $t_d(\vec{r},\vec{r}')$ is the signal delay time

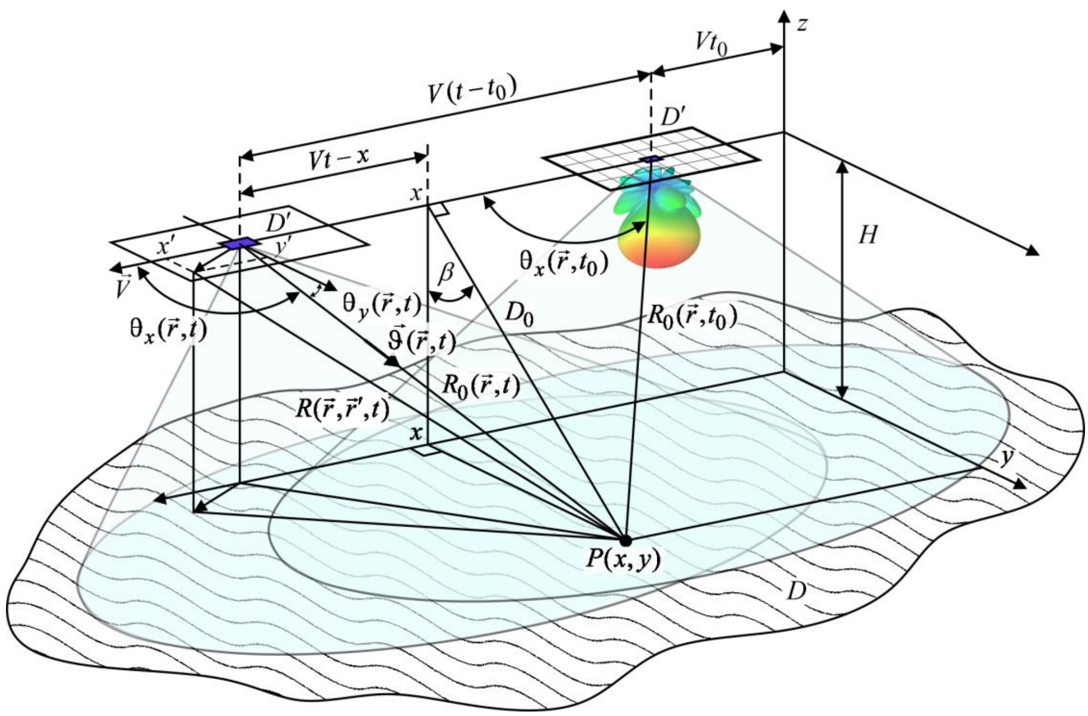


Fig. 1. Surface sensing geometry

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

during propagation from the transmitting antenna to the surface and vice versa. A unit signal (3) is determined by the geometry of the sensing, the shape of the sounding signal, and the movement of the region D' relative to D.

The correlation function of the scattering coefficient $\dot{F}(\vec{r})$ is related to the desired RCS as follows:

$$\sigma^0(\vec{r}) = \int_D < \dot{F}(\vec{r})\dot{F}^*(\vec{r}+\Delta\vec{r}) > e^{-jq_\perp \Delta\vec{r}} d\Delta\vec{r} = \\ = \int_D \dot{R}_{\dot{F}}(\vec{r},\Delta\vec{r}) e^{-jq_\perp \Delta\vec{r}} d\Delta\vec{r}, \quad (4)$$

where $\dot{R}_{\dot{F}}(\vec{r},\Delta\vec{r})$ is the spatial correlation function of $\dot{F}(\vec{r})$, $q_\perp$ is the scattering vector.

According to Fig. 1 signal (3) can be specified in the following form:

$$\dot{s}_0(t,\vec{r},\vec{r}') = \dot{S}_0(t,\vec{r},\vec{r}')\exp\left(j2\pi f_0 t\right), \quad (5)$$

where

$$\dot{S}_0(t,\vec{r},\vec{r}') = \varepsilon\dot{I}(\vec{r}')\exp(j2k\vec{\vartheta}(\vec{r},t)\vec{r}')\dot{A}(t-2R_0(\vec{r},t)c^{-1})\times \\ \times\exp(j2k(V(t-t_0)\cos\theta_x(\vec{r},t_0)))\times \\ \times\exp(-jk[V^2(t-t_0)^2 R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)]), \quad (6)$$

$$\vec{\vartheta}(\vec{r},t) = (\vartheta_x(\vec{r},t) = \cos\theta_x(\vec{r},t), \vartheta_y(\vec{r},t) = \cos\theta_y(\vec{r},t))$$

is the vector of directed cosines that change in time with the movement of the aircraft, $R_0(\vec{r},t)$ is the distance from the surface element $P(x,y)$ to the antenna phase center.

Analysis of the statistical characteristics of the received signal and noise

For a statistical description of the received signals and noise, we can write the observation equation in the following form

$$u(t,\vec{r}') = \mathrm{Re}\,\dot{s}(t,\vec{r}') + n(t,\vec{r}'), \quad (7)$$

where $n(t,\vec{r}')$ is the white noise with correlation function

$$R_n(t_1,t_2,\vec{r}_1',\vec{r}_2') = 0,5N_{0n}\delta(t_1-t_2)\delta(\vec{r}_1'-\vec{r}_2'). \quad (8)$$

It is assumed that the spectral density of the noise N_{0n} in each element of the antenna is the same.

The correlation function of the real received signal has the form

$$R_s(t_1,t_2,\vec{r}_1',\vec{r}_2') = \\ 0,5\,\mathrm{Re}\int_D \sigma^0(\vec{r})\dot{s}_0(t_1,\vec{r},\vec{r}_1')\dot{s}_0^*(t_2,\vec{r},\vec{r}_2')d\vec{r}. \quad (9)$$

Based on (8) and (9), we will write the correlation functions for the entire observation equation

$$R_u(t_1,t_2,\vec{r}_1',\vec{r}_2') = \\ = 0,5\,\mathrm{Re}\int_D \sigma^0(\vec{r})\dot{s}_0(t_1,\vec{r},\vec{r}_1')\dot{s}_0^*(t_2,\vec{r},\vec{r}_2')d\vec{r} + \\ +0,5N_{0n}\delta(t_1-t_2)\delta(\vec{r}_1'-\vec{r}_2'). \quad (10)$$

RCS is determined by expression (4) and is a spectral statistical characteristic (power spectral density) of a statistically heterogeneous random process $\dot{F}(\vec{r}_1)$. It is the desired surface parameter and the desired image in scatterometric radars. This parameter is contained not directly in the observation equation, as it is usually in the classical synthesis of aperture, but in its correlation and inverse correlation functions.

Solution of the optimization problem

From the stochastic reflected signals $\dot{s}(t,\vec{r}')$ received by each element of the antenna array D' and observed against additive Gaussian noise $n(t,\vec{r}')$ it is necessary to estimate the RCS $\sigma^0(\vec{r})$ of the underlying surface in the SAR scatteromer with a planar antenna array in an optimal way.

We will obtain the optimal estimation algorithm of $\sigma^0(\vec{r})$ by the maximum likelihood method. We write the likelihood functional for the stochastic model of received signals in the following form:

$$P[u(t,\vec{r}')\,|\,\sigma^0(\vec{r})] = \kappa[\sigma^0(\vec{r})]\times \\ \times\exp\left\{ -0,5\int_T\int_T\int_{D'}\int_{D'} u(t_1,\vec{r}_1')W(t_1,t_2,\vec{r}_1',\vec{r}_2',\sigma^0(\vec{r}))\times \\ \times u(t_2,\vec{r}_2')dt_1dt_2d\vec{r}_1'd\vec{r}_2' \right\}, \quad (11)$$

where $\kappa[\sigma^0(\vec{r})]$ is the coefficient depending on the desired energy parameter $\sigma^0(\vec{r})$, T is the observation time, $W(t_1,t_2,\vec{r}_1',\vec{r}_2',\sigma^0(\vec{r}))$ is the inverse correlation function, which is found from the inverse integral equation

$$\int\limits_T \int\limits_{D'} R_u(t_1, t_2, \vec{r}_1', \vec{r}_2', \sigma^0(\vec{r}))W(t_2, t_3, \vec{r}_2', \vec{r}_3', \sigma^0(\vec{r}))d\vec{r}_2' dt_2 = \\ = \delta(t_1 - t_3)\delta(\vec{r}_1' - \vec{r}_3'). \quad (12)$$

Parameter $\sigma^0(\vec{r})$ depends on the coordinates $\vec{r}$ then the problem of finding the maximum of functional (11) must be solved by variational methods. Since the exponent and its argument are monotonously related to each other instead of the likelihood functional (11) we will differentiate its logarithm and equate the result to zero:

$$\delta \ln P[u(t, \vec{r}') \,|\, \sigma^0(\vec{r})] / \delta\sigma^0(\vec{r})\Big|_{\sigma^0(\vec{r}) = \sigma^0_{opt}(\vec{r})} = 0. \quad (13)$$

In (13) δ is the symbol of the variational derivative.

As a result of differentiation (11), we obtain the following equation

$$\left|\dot{Y}(\vec{r})\right|^2 = \frac{1}{2}\int\limits_D \sigma^0(\vec{r}_1) \,|\, \dot{\Psi}_W(\vec{r}, \vec{r}_1)\,|^2\, d\vec{r}_1 + N_{0n}\, Э_W(\vec{r}), \quad (14)$$

where

$$\dot{Y}(\vec{r}) = \int_T \int_{D'} u(t_1, \vec{r}_1')\dot{s}_{0W}[t_1, \vec{r}_1', \sigma^0(\vec{r})]d\vec{r}_1' dt_1 \quad (15)$$

is the optimal output effect of the modified scatterometric SAR,

$$Э_W(\vec{r}) = 0,5\int_T \int_{D'} |\dot{s}_{0W}(t_3, \vec{r}, \vec{r}_3')\,|^2\, d\vec{r}_3'\, dt_3 \quad (16)$$

is the energy of the reference signal $\dot{s}_{0W}[t_1, \vec{r}_1', \sigma^0(\vec{r})]$,

$$\dot{\Psi}_W(\vec{r}, \vec{r}_1) = \int_T \int_{D'} \dot{s}_0(t_1, \vec{r}, \vec{r}_1')\, \overset{*}{\dot{s}}_{0W}(t_1, \vec{r}_1, \vec{r}_1')d\vec{r}_1' dt_1 \quad (17)$$

is the ambiguity function of the scatterometric SAR with a planar antenna array determining its resolution,

$$\dot{s}_{0W}[t_1, \vec{r}_1', \sigma^0(\vec{r})] = \\ = \int_T \int_{D'} W(t_1, t_3, \vec{r}_1', \vec{r}_3', \sigma^0(\vec{r}))\dot{s}_0(t_3, \vec{r}, \vec{r}_3')d\vec{r}_3'\, dt_3 \quad (18)$$

is the reference signal in the synthesized optimal algorithm.

Expression (15) is the basis of the modified aperture synthesis algorithm in airborne radars with antenna arrays. Unlike the classical aperture synthesizing algorithm [13-16] the modified algorithm additionally performs decorrelation of signals reflected from the surface, which consists in integrating them with weight $W(t_1, t_3, \vec{r}_1', \vec{r}_3', \sigma^0(\vec{r}))$. As a result of this, the characteristic speckle intervals (spot sizes) will be significantly smaller than with classical aperture synthesis. Therefore, their subsequent smoothing with the same efficiency can be performed with windows of smaller width, which ultimately allows to increase the resolution of the scatterometer. The decorrelation procedure provides a certain superresolution and can be performed using an inverse filter with an impulse response $W(t_1, t_3, \vec{r}_1', \vec{r}_3', \sigma^0(\vec{r}))$, which is usually used to solve incorrect inverse problems of restoring various functions and, in particular, images.

Physical interpretation of the obtained analytical expressions

In order to better understand the physical nature of the obtained method for synthesizing aperture in airborne scatterometers with antenna arrays we assume that the integration time T and the integration region D' are small, but significantly exceed the width of the correlation function (10) in time and space coordinates. Then the analysis of many expressions can be carried out by the Fourier transform method either in infinite limits, or in current (moving) finite ones, but considering the current finite limits significantly exceeding the width of the correlation function and assuming that the results obtained at finite integration intervals and conditionally infinite practically coincide. This method of applying Fourier transforms is called the method of frozen parameters in the study of non-stationary statistically heterogeneous random processes, with relatively slow changes in their statistical characteristics. We will call such processes locally stationary or locally statistically homogeneous, and Fourier transforms with such locally current limits in time are short-term or window ones (with a rectangular window corresponding to the current limits of integration), and in space - short-scale ones.

For further analysis (15), we rewrite a unit signal in the following form

$$\dot{S}_0(t, \vec{r}, \vec{r}') = \dot{S}_0(t, \vec{r})\; \dot{I}(\vec{r}')\exp(j2k\vec{\vartheta}(\vec{r}, t)\vec{r}'), \quad (19)$$

where

$$\dot{S}_0(t, \vec{r}) = \varepsilon\,\dot{A}(t - 2R_0(\vec{r}, t)c^{-1}) \times \\ \times \exp(j2k(V(t - t_0)\cos\theta_x(\vec{r}, t_0))) \times \\ \times \exp(-jk(V^2(t - t_0)^2 R_0^{-1}(\vec{r}, t_0)\sin^2\theta_x(\vec{r}, t_0))) . \quad (20)$$

According to the presented unit signal we will write the optimal output effect in the following form

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

$$\dot{Y}(\vec{r}) = 0,5\int_T\int_T \dot{S}_0^*(t_3,\vec{r})\int_{D'}\int_{D'}\dot{U}(t_1,\vec{r}_1')\times$$
$$\times\dot{I}^*(\vec{r}_3')W(t_1,t_3,\vec{r}_1',\vec{r}_3',\sigma^0(\vec{r}))\times$$
$$\times\exp(-j2k\vec{\vartheta}(\vec{r},t_3)\vec{r}_3')\,d\vec{r}_3'\,d\vec{r}_1'dt_1dt_3. \qquad (21)$$

For a physical interpretation of the obtained algorithm (21), we divide the procedure of imaging into two stages: spatial and temporal processing.

Spatial processing. At coinciding moments in time $t_1 = t_3 = t$ (at the current time t), spatial processing is determined by the internal integral of expression (21) over the variables $d\vec{r}_3'\,d\vec{r}_1'$

$$\dot{Y}_{D'}(t,\vec{r}) = \int_{D'}\int_{D'}\dot{U}(t,\vec{r}_1')\,W(t,\vec{r}_1',\vec{r}_3',\sigma^0(\vec{r}))\times$$
$$\times\dot{I}^*(\vec{r}_3')\exp(-j2k\vec{\vartheta}(\vec{r},t)\vec{r}_3')d\vec{r}_3'd\vec{r}_1' =$$
$$= \int_{D'}\dot{U}(t,\vec{r}_1')\,\dot{I}_W^{\,*}(t,\vec{r}_1',\vec{r})d\vec{r}_1', \qquad (22)$$

where

$$\dot{I}_W^*(t,\vec{r}_1',\vec{r}) =$$
$$= \int_{D'}W(t,\vec{r}_1',\vec{r}_3',\sigma^0(\vec{r}))\dot{I}^*(\vec{r}_3')\exp(-j2k\vec{\vartheta}(\vec{r},t)\vec{r}_3')d\vec{r}_3' \qquad (23)$$

is the amplitude-phase distribution of the transfer coefficient of the elements of the antenna system aperture.

The Fourier transform of (23) is the radiation pattern of the antenna system

$$F\left\{\dot{I}(t,\vec{r}_1',\vec{r})\right\} =$$
$$= F_{\vec{r}'}\{W(t,\vec{r}',\sigma^0(\vec{r}))\}\cdot F_{\vec{r}'}\{\dot{I}^*(\vec{r}')\exp(-j2k\vec{\vartheta}(\vec{r},t)\vec{r}')\}, \qquad (24)$$

where $F_{\vec{r}'}\{\cdot\}$ is the operator of the Fourier transform in spatial coordinates.

The first factor is a spatial decorrelation filter with a spatial characteristic

$$G_W(t,\vec{\vartheta}(\vec{r},t)) =$$
$$= \sigma^0(\vec{\vartheta}(\vec{r},t))|\,\dot{S}_0(t,\vec{\vartheta}(\vec{r},t))\,|^2 + 0,5N_{0n}, \qquad (25)$$

where $\dot{S}_0(t,\vec{\vartheta}(\vec{r},t))$ is the spectrum of (20).

The second factor of expression (24) is the radiation pattern of an antenna with amplitude-phase distribution $\dot{I}^*(\vec{r}')$ shifted on coordinate $\vec{\vartheta}$ by a value $\vec{\vartheta}(\vec{r},t)$. Physically, this factor indicates the procedure for the formation of many radiation patterns oriented to each point on the surface $\vec{r}$ and changing their angular direction as the aircraft moves creating a focusing effect on each point $P(x,y)$ on the surface. By selection $\dot{I}^*(\vec{r}')$ the shape of the antenna pattern can be adjust. This type of review allows you to increase the observation time and expand the range of viewing angles.

Taking into account (25) the expression (22) will be

$$\dot{Y}_{D'}(t,\vec{r}) =$$
$$= F_{\vec{r}'}^{-1}\left\{\frac{\dot{U}(t,\vec{\vartheta}(\vec{r},t))\dot{F}_{D'}(\vec{\vartheta}(\vec{r},t))}{\sigma^0(\vec{\vartheta}(\vec{r},t))|\,\dot{S}_0(t,\vec{\vartheta}(\vec{r},t))\,|^2 + 0,5N_{0n}}\right\}. \qquad (26)$$

The numerator of expression (26) indicates the selectivity of the antenna array in angular coordinates in the form of a radiation pattern. The denominator extends the observation area limited by the antenna array radiation pattern due to inverse filtering in the filter $W(t,\vec{r}',\sigma^0(\vec{r}))$.

Temporal processing. The temporal processing in (21) is defined at some point $\vec{r}_1' = \vec{r}_3' = \vec{r}' = 0$ in the following form

$$\dot{Y}(\vec{r}) = 0,5\int_T \dot{U}(t_1)\int_T \dot{S}_0^*(t_3,\vec{r})W(t_1,t_3,\sigma^0(\vec{r}))dt_3dt_1. \qquad (27)$$

We will find the inverse correlation function using the inverse Fourier transform

$$W[\tau,\sigma^0(\vec{r})] = F_T\{G_R^{-1}[\omega,\sigma^0(\vec{r})]\} =$$
$$= F_T\{(\sigma^0(\vec{r})\,|\,\dot{S}_0(j\omega)\,|^2 + 0,5N_{0n})^{-1}\}. \qquad (28)$$

where $G_R[\omega,\sigma^0(\vec{r})]$ is the Fourier transform of correlation function (10) at some point $\vec{r}_1' = \vec{r}_3' = \vec{r}' = 0$.

Taking into account (28), algorithm (27) in spectral domain takes the form

$$\dot{Y}(\vec{r}) = F_T^{-1}\{\frac{\dot{U}(j\omega)\dot{S}_0^*(j\omega,\vec{r})}{\sigma^0(\vec{r})\,|\,\dot{S}_0(j\omega)\,|^2 + 0,5N_{0n}}\}. \qquad (29)$$

In (29) $\dot{U}(j\omega) = F_T\{\dot{U}(t,\vec{r}'=0)\}$ and $\dot{S}_0^*(j\omega,\vec{r})$ is the spectrum of signals reflected from each point on the surface with coordinates $\vec{r}$. From the analysis of expression (29) it follows that the numerator corresponds to the classical method of synthesizing the aperture in the form of coordinated processing of received signals with a reference signal. The transmission coefficient modulus of this matched filter and the spectrum modulus of a unit signal are the same, but the phase characteristics are opposite, which indicates that such a filter equalizes the phases of all spectral components of the received signal and performs their coherent addition (accumulation). The denominator describes the operation of an inverse filter with an impulse response (28).

The gain of the inverse filter increases at those frequencies at which the spectral components of the received signal are reduced. As a result, the effective spectrum width of the received oscillations expands. The addition $0,5N_{0n}$ in the denominator that eliminates the incorrect division by zero operation and is a regularizer of this unconventional statistical solution inverse problem of $\sigma^0(\vec{r})$ recovery. An inverse filter decorrelates the received signal making it closer to white noise.

Block diagram of optimal SAR

The optimal method (21) is general and can be used for solution of many problems of estimating the parameters of useful signals. However, the general expression in solving a particular problem acquires a number of new properties that characterize the features of the construction of algorithms for a particular geometry of the problem. Assume that the registration area of the reflected signals is discrete, consisting of a set of elementary antennas, which together form an antenna array. The model of the observation equation for such a discrete aperture is:

$$u(t,\vec{r}'_m) = \mathrm{Re}\dot{s}(t,\vec{r}'_m) + n(t,\vec{r}'_m), \quad m=\overline{1,M}. \qquad (30)$$

We represent the inverse correlation function $W(t_1,t_3,\vec{r}'_1,\vec{r}'_3,\sigma^0(\vec{r}))$ for the discrete aperture in the form

$$W(t_1,t_3,\vec{r}'_1,\vec{r}'_3,\sigma^0(\vec{r})) = W_{mn}(t,\sigma^0(\vec{r}))\cdot W(t_1,t_3,\sigma^0(\vec{r})),$$
$$m=\overline{1,M},\ n=\overline{1,N}. \qquad (31)$$

In this case, algorithm (21) taking into account (31) can be written in the vector-matrix form

$$\dot{Y}(\vec{\vartheta}(\vec{r})) = 0,5\int_T \dot{S}_0^*(t_3,\vec{r})\int_T W(t_1,t_3,\sigma^0(\vec{r}))\times$$
$$\times\sum_{n=1}^{N}[\sum_{m=1}^{M}\dot{U}_m(t_1)W_{mn}(t_1,\sigma^0(\vec{r}))]\times$$
$$\times\dot{I}_n^*\exp(-j2k\vec{\vartheta}(\vec{r},t_1)\vec{r}'_n)\,dt_1dt_3 \qquad (32)$$

or matrix form

$$\dot{Y}(\vec{\vartheta}(\vec{r})) = 0,5\int_T \dot{S}_0^*(t_3,\vec{r})\int_T W(t_1,t_3,\sigma^0(\vec{r}))\times$$
$$\times(\dot{\vec{U}}^T(t_1)\underline{W}(t_1,\sigma^0(\vec{r}))\dot{\vec{E}}(\vec{r},t_1))\,dt_1dt_3, \qquad (33)$$

where $\dot{U}(t_1)$ is the column vector of the signals received by the antenna array of dimension $m\times 1$, $(\cdot)^T$ is the transpose sign, $\underline{W}(t_1,\sigma^0(\vec{r}))$ is the matrix of the spatial whitening filter of dimension $m\times n$, $\dot{\vec{E}}(\vec{r},t_1) = \dot{I}_n^*\exp(-j2k\vec{\vartheta}(\vec{r},t_1)\vec{r}'_n)$ is the column vector of amplitude-phase distribution and phase shifts of dimension $n\times 1$.

One of the possible schemes of a quasi-optimal RCS estimation is shown in Fig. 2.

The essence of received field $\dot{U}_{mn}(t)$ processing according to (33) is as follows. Initially, the received oscillations from the output of each element of antenna array are processed in a spatial filter with an impulse response $\dot{I}_{mn}^*$. Then the spatio-temporal signals are whitened in the spatial filter $W_{mn}(t_1,\sigma^0(\vec{r}))$. The resulting signals are processed in a beam synthesizer that performs a spatial discrete Fourier transform and forms a family of beams. As the aircraft moves, each individual beam, at each moment of time t, moves in space so that its maximum is always directed at a selected point on the surface. The next stage of processing is decorrelation of signals over time in a filter with an impulse response $W(t_1,t_3,\sigma^0(\vec{r}))$. In the matched filter block, the amplitudes of the received and decorrelated signals from directions $\vec{\vartheta}(\vec{r})$ are coherently detected and the reflected signals are coherently accumulated along the flight path of the aircraft. Coherent phase shift in the reference signal leads to the formation of an artificial aperture, the length of which is equal to the product of the speed of the aircraft and the synthesis time. In this case, the synthesis time is determined by the time of focusing on the selected point on the surface.

Statistical modeling of the proposed method

For validation of the proposed method SAR images were simulated according to the phenomenological description of the electromagnetic field [11, 12].

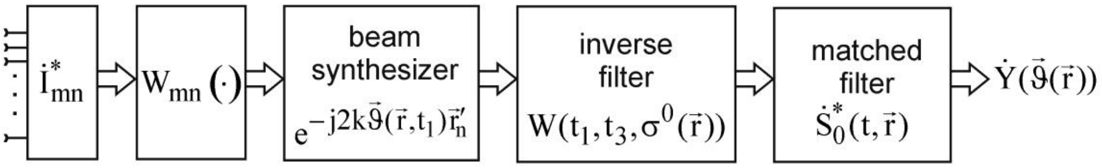
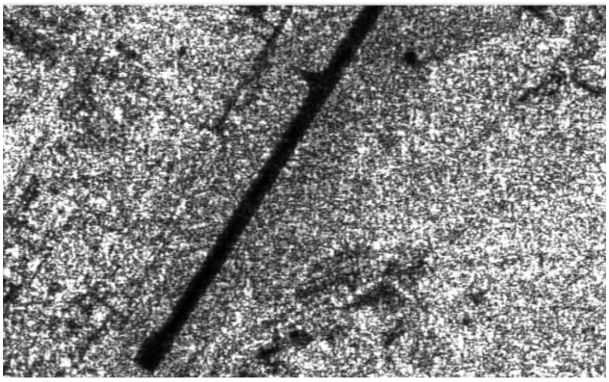


Fig. 2. Block diagram of optimal RCS estimation in SAR

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

Test image is shown in the Fig. 3, a. Simulated SAR image with coherent processing without decorrelation is depicted in the Fig. 3, b. Result of proposed method simulation is shown in the Fig. 3, c.


a


b

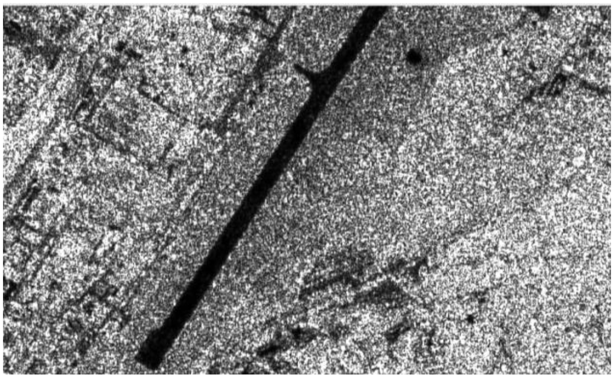

c

Fig. 3. Block diagram of optimal RCS estimation in SAR Result of SAR images simulation: a – test image, b – coherent processing without decorrelation filters, c – proposed optimal method

For quantitative estimation of the signal processing quality the full-reference quality metrics [16, 17] were used. The result of averaging of 1000 estimations is shown in the Table 1.

From the analysis of the results in Table 1 it flows that propose method has higher quality and smaller size of spackle noise. This result was achieved due to the use of the operation of decorrelation of the received signals. The level of the decoration and superresolution of aerospace radar depends on the signal-to-noise value, the type of the transmitting signal, the parameters of the antenna array, the geometry of the surface measurements and the observation area. This result provides wide opportunities to change the parameters of signal processing and can be used to describe the receiving path of a cognitive radar.

Table 1

Quantitative estimation of SAR imaging

Imaging method	Full-reference quality metrics		
	MSE	pSNR	SSIM
Coherent processing without decorrelation	$4{,}1259 \cdot 10^3$	11,9756	0,1245
Proposed optimal signal processing	$4{,}0514 \cdot 10^3$	12,0547	0,1326

Conclusions

The synthesized optimal method of signal processing in radar scatterometers is a generalization of already existing methods for the operation of SARs with planar antenna arrays. The generalized method consists in underlying surface observation and modified matched filtering with the decorrelation operation. The application of this method simultaneously allows to expand the continuous observation region and increase the resolution in spatial coordinates. From the analysis of the frequency characteristics of the decorrelating filters it follows that the resolution of the synthesized scatterometer is inversely proportional to the signal-to-noise ratio.

Acknowledgement. The work was supported by the Ministry of Education and Science of Ukraine, the state registration numbers of the projects are 0120U102082, 0119U100968 and 0121U109600.

Future research directions

Future research should be devoted to radar cross section estimation in synthetic aperture radar with planar antenna array in the presence of electromagnetic jamming.

References (GOST 7.1:2006)

1. Space-borne Earth surveillance radar systems [Text] / V. S. Verba, L. B. Neronskiy, I. G. Osipov, V. E. Turuk. – M. : Radiotechnika, 2010. – 680 p.

2. Maitre, H. Processing of synthetic aperture radar (SAR) images [Text] / H. Maitre. – NY. : Wiley-ISTE, 2008. – 384 p.

3. Potential of high-resolution SAR images for ur-

ban analysis [Text] / U. Soergel, E. Michaelsen, U. Thoennessen, U. Stilla // Proc. ISPRS Archives vol. 36, part 3/W24, Vienna, Austria, 2005. – P. 149–154.

4. Волосюк, В. К. Статистическая теория радиотехнических систем дистанционного зондирования и *радиолокации [Текст] / В. К. Волосюк, В. Ф. Кравченко. – М. : Физматлит, 2008. – 704 с.*

5. Review of modern algorithms for high resolution imaging with passive radar [Text] / V. K. Volosyuk, V. F. Kravchenko, B. G. Kutuza, V. V. Pavlikov // International Conference on Antenna Theory and Techniques. ICATT-2015. – Kharkiv, 2015. – P. 1-6.

6. Kravchenko, V. F. Statistical Synthesis of Optimal and Quasi-optimal Chopper Radiometers [Electronik resource] / V. F. Kravchenko, V. K. Volosyuk, V. V. Pavlikov // Progress In Electromagnetics Research Symposium Proceedings. PIERS-2012, Aug. 19–23, 2012, Moscow, Russia. – 2012. – P. 50–54. – Access mode: http://piers.org/piersproceedings/piers2012Proc.php – 12.12.2020.

7. Quasioptimal Spatiotemporal Signal Processing Algorithm for Radar Imaging [Text] / V. V. Pavlikov, M. V. Nechyporuk, Nguyen Van Huu, A. D. Sobkolov // Modern Problems of Radio Engineering, Telecommunications, and Computer Science. TCSET-2020. – Lviv-Slavsko, 2018. – P. 8-11.

8. Volosyuk, V. K. Phenomenological Description of the Electromagnetic Field and Coherent Images in Radio Engineering and Optical Systems [Text] / V. K. Volosyuk, V. V. Pavlikov, S. S. Zhyla // IEEE 17th International Conference on Mathematical Methods in Electromagnetic Theory MMET-2018. – Kiev, 2018. – P. 302-305.

9. Volosyuk, V. K. Phenomenological description of coherent radar images based on the concepts of the measure of set and stochastic integral [Text] / V. K. Volosyuk, S. S. Zhila, D. V. Kolesnikov // Telecommunications and Radio Engineering. – 2019. – No. 78(1). – P. 19–30. DOI: 10.1615/telecomradeng.v78.i1.30.

10. Munson, D. C. A signal processing view of strip-mapping synthetic aperture radar [Text] / D. C. Munson, R. L. Visentin // IEEE Transactions on Acoustics, Speech, and Signal Processing. – 1989. – Vol. 37, no. 12. – P. 2131-2147. DOI: 10.1109/29.45556.

11. Brown, W. M. Sighted automation and fine resolution imaging [Text] / W. M. Brown, J. L. Walker, W. R. Boario // IEEE Transactions on Aerospace and Electronic Systems. – 2004. – Vol. 40, no. 4. – P. 1426-1445. DOI: 10.1109/TAES.2004.1386898.

12. Curlander, J. C. Synthetic Aperture Radar: System and Signal Processing [Text] / J. C. Curlander, R. N. McDonough. – NY. : John Wiley & Sons, 1991. – 672 p.

13 Sullivan, R. J. Microwave Radar Imaging and Advanced Concepts [Text] / R. J. Sullivan. – Boston : Artech House, 2000. – 496 p.

14. Методика определения поля обнаружения беспилотных летательных аппаратов наземным наблюдателем [Текст] / С. К. Абрамов, В. В. Абрамова, К. Д. Абрамов, В. В. Лукин, В. В. Бондарь, И. В. Калужинов // Радіоелектронні і комп'ютерні системи. – 2020. – № 3(95). – С. 36-42. DOI: 10.32620/reks.2020.3.04.

15. Єремеєв, О. І. Комбінована метрика візуальної якості зображень дистанційного зондування на основі нейронної мережі [Текст] / О. І. Єремеєв, В. В. Лукін, К. Окарма // Радіоелектронні і комп'ютерні системи. – 2020. – № 4(96). – С. 4-15. DOI: 10.32620/reks.2020.4.01.

References (BSI)

1. Verba, V. S., Neronskiy, L. B., Osipov, I. G., Turuk, V.E. *Space-borne Earth surveillance radar systems*. Moscow, "Radiotechnika" Publ., 2010. 680 p.

2. Maitre, H. Processing of synthetic aperture radar (SAR). NY., Wiley-ISTE Publ., 2008. 384 p.

3. Soergel, U., Michaelsen, E., Thoennessen, U., Stilla, U. Potential of high-resolution SAR images for urban analysis. *Proc. ISPRS Archives*, 2005, vol. 36, part 3/W24, pp. 149–154.

4. Volosyuk, V. K., Kravchenko, V. F. *Statisticheskaya teoriya radiotekhnicheskikh sistem distantsionnogo zondirovaniya i radiolokatsii* [Statistical Theory of Radio-Engineering Systems of Remote Sensing and Radar]. Moscow, Fizmatlit Publ., 2008. 740 p.

5. Volosyuk, V. K., Kravchenko, V. F., Kutuza, B. G., Pavlikov V. V. Review of modern algorithms for high resolution imaging with passive radar. *International Conference on Antenna Theory and Techniques (ICATT-2015)*, Kharkiv, 2015, pp. 1-6.

6. Kravchenko, V. F., Volosyuk, V. K., Pavlikov, V. V. Statistical Synthesis of Optimal and Quasi-optimal Chopper Radiometers. *Progress In Electromagnetics Research Symposium Proceedings. (PIERS-2012).* Moscow, 2012, pp. 50–54. Access mode: http://piers.org/piersproceedings/piers2012Proc.php. (accessed 12.12.2020).

7. Pavlikov, V. V., Nechyporuk, M. V., Nguyen Van Huu, Sobkolov, A. D. Quasioptimal Spatiotemporal Signal Processing Algorithm for Radar Imaging. *Modern Problems of Radio Engineering, Telecommunications, and Computer Science (TCSET-2020)*, Lviv-Slavsko, 2018, pp. 8-11.

8. Volosyuk, V. K., Pavlikov, V. V., Zhyla, S. S. Phenomenological Description of the Electromagnetic Field and Coherent Images in Radio Engineering and Optical. *IEEE 17th International Conference on Mathematical Methods in Electromagnetic Theory (MMET-2018)*, Kiev, 2018, pp. 302-305.

9. Volosyuk, V. K., Zhila, S. S., Kolesnikov, D. V. Phenomenological description of coherent radar images based on the concepts of the measure of set and stochastic integral. *Telecommunications and Radio Engineering*, no. 78(1), 2019, pp. 19–30. DOI: 10.1615/ telecomradeng.v78.i1.30.

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

10. Munson, D. C., Visentin, R. L. A signal processing view of strip-mapping synthetic aperture radar. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 1989, vol. 37, no. 12, pp. 2131-2147. DOI: 10.1109/29.45556.

11. Brown, W. M., Walker, J. L., Boario, W. R. Sighted automation and fine resolution imaging. *IEEE Transactions on Aerospace and Electronic Systems,* 2004, vol. 40, no. 4, pp. 1426- 1445. DOI: 10.1109/ TAES.2004.1386898.

12. Curlander, J. C., McDonough, R. N. *Synthetic Aperture Radar: System and Signal Processing.* NY., John Wiley & Sons Publ., 1991. 672 p.

13. Sullivan, R. J. *Microwave Radar Imaging and Advanced Concepts*. Boston, Artech House Publ., 2000. 496 p.

14. Abramov, S. K., Abramova, V. V., Abramov, K. D., Lukin, V. V., Bondar, V. V., Kaluzhinov, I. V. Metodika opredelenija polja obnaruzhenija bespilotnyh letatel'nyh apparatov nazemnym nabljudatelem [Technique of detection field estimating for unmanned aerial vehicles by a ground observer]. *Radioelektronni i komp'uterni sistemi – Radioelectronic and computer systems,* 2020, no. 3(95), pp. 36-42. DOI: 10.32620/reks.2020.3.04.

15. Ieremeiev, O., Lukin, V., Okarma, K. Kombinovana metryka vizual'noyi yakosti zobrazhen' dystantsiynoho zonduvannya na osnovi neyronnoyi merezhi [Combined visual quality metric of remote sensing images based on neural network]. *Radioelektronni i komp'uterni sistemi – Radioelectronic and computer systems,* 2020, no. 4(96), pp. 4-15. DOI: 10.32620/reks.2020.4.01.

Надійшла до редакції 4.01.2021, розглянута на редколегії 16.02.2021

ОПТИМАЛЬНА ОЦІНКА ЕФЕКТИВНОГО ПЕРЕРІЗУ РОЗСІЮВАННЯ В РАДІОЛОКАЦІЙНИХ СИСТЕМАХ З СИНТЕЗУВАННЯМ АПЕРТУРИ ТА ПЛАНАРНОЮ АНТЕННОЮ РЕШІТКОЮ

В. К. Волосюк, С. С. Жила, В. В. Павліков, Д. С. Власенко,
В. В. Кошарський, Д. В. Колесніков, О. С. Інкарбаєва, К. М. Нежальська

Вирішено оптимізаційну задачу статистичного синтезу методу оцінки ефективного перерізу розсіяння в РЛС із синтезованою апертурою і планарною антенною решіткою. Необхідний радіолокаційний ефективний переріз розсіювання задається як статистична характеристика просторово-неоднорідного комплексного коефіцієнта розсіювання середовища, що підлягає дослідженню. Фактично розробляються нові методи розв'язання обернених задач не стосовно відновлення когерентних зображень у вигляді просторового розподілу комплексного коефіцієнта розсіювання, а щодо оцінювання статистичних характеристик неоднорідних (просторово нестаціонарних) випадкових процесів. Електрофізичні параметри поверхонь і їх статистичні характеристики розглядаються як функції просторових координат. В якості методу оптимізації був обраний метод максимальної правдоподібності. Отримані результати дозволяють визначити багатоканальну структуру, оптимальний метод огляду поверхні і потенційне просторову роздільну здатність в аерокосмічних скаттерометричних радарах з антенною решіткою. Визначено оптимальні операції для обробки просторово-часових сигналів і запропоновано модифікований метод синтезу апертури антени, який, на відміну від класичного алгоритму для синтезу апертури антени, що складається в інтегруванні добутку значень прийнятого сигналу і опорного сигналу (одиничного сигналу), додатково реалізує декореляцію сигналів, що віддзеркалені від земної поверхні. Нова операція декорреляції розсіяних сигналів полягає в їх інтегруванні зі зворотною просторово-часовою кореляційною функцією. Для підтвердження достовірності отриманих результатів було проведено імітаційне моделювання класичного методу синтезу когерентних зображень і запропонованого оптимального методу. З аналізу результатів випливає, що запропонований метод має більш високу якість і менший розмір спекл-шуму. Отримані в статті результати можуть бути використані для розробки і обґрунтування вимог до тактико-технічних характеристик перспективних аерокосмічних скаттерометричних радарів з плоскими фазованими антенними решітками.

Ключові слова: радар з синтезованою апертурою; ефективний переріз розсіювання; статистична оптимізація.

ОПТИМАЛЬНАЯ ОЦЕНКА ЭФФЕКТИВНОГО СЕЧЕНИЯ РАССЕЯНИЯ В РАДИОЛОКАЦИОННОЙ СИСТЕМОЙ С СИНТЕЗИРОВАННОЙ АПЕРТУРОЙ И ПЛАНАРНОЙ АНТЕННОЙ РЕШЕТКОЙ

В. К. Волосюк, С. С. Жила, В. В. Павликов, Д. С. Власенко,
В. В. Кошарский, Д. В. Колесников, О. С. Инкарбаева, К. Н. Нежальская

Решена оптимизационная задача статистического синтеза метода оценки эффективного сечения рассеяния в РЛС с синтезированной апертурой и планарной антенной решеткой. Требуемое радиолокационное эффективное сечения рассеяния задается как статистическая характеристика пространственно-неоднородного комплексного коэффициента рассеяния исследуемой среды. Фактически разрабатываются новые методы решения обратных задач не в отношении восстановления когерентных изображений в виде пространственного распределения комплексного коэффициента рассеяния, а в отношении оценивания статистических характеристик неоднородных (пространственно нестационарных) случайных процессов. Электрофизические параметры поверхностей и их статистические характеристики рассматриваются как функции пространственных координат. В качестве метода оптимизации был выбран метод максимального правдоподобия. Полученные результаты позволяют определить многоканальную структуру, оптимальный метод обзора поверхности и потенциальное пространственное разрешение в аэрокосмических скаттерометрических радарах с антенной решеткой. Определены оптимальные операции для обработки пространственно-временных сигналов и предложен модифицированный метод синтеза апертуры антенны, который, в отличие от классического алгоритма для синтеза апертуры антенны, состоящего в интегрировании произведения значений принимаемого сигнала и опорного сигнала (единичного сигнала), дополнительно реализует декорреляцию сигналов, отраженных от земной поверхности. Новая операция декорреляции рассеянных сигналов заключается в их интегрировании с обратной пространственно-временной корреляционной функцией. Для подтверждения достоверности полученных результатов было проведено имитационное моделирование классического метода синтеза когерентных изображений и предложенного оптимального метода. Из анализа результатов следует, что предлагаемый метод имеет более высокое качество и меньший размер спекл-шума. Полученные в статье результаты могут быть использованы для разработки и обоснования требований к тактико-техническим характеристикам перспективных аэрокосмических скаттерометрических радаров с плоскими фазированными антенными решетками.

Ключевые слова: радар с синтезированной апертурой; эффективное сечение рассеяния; статистическая оптимизация.

Волосюк Валерій Костянтинович – д-р техн. наук, проф., проф. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Жила Семен Сергійович – канд. техн. наук, зав. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Павліков Володимир Володимирович – д-р техн. наук, старш. наук. співроб., проректор з наукової роботи, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Власенко Дмитро Сергійович – асист. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Кошарський Володимир Віталійович – асист. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Колесніков Денис Вікторович – асист. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Інкарбаєва Ольга Сергіївна – асист. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Нежальська Ксенія Миколаївна – канд. техн. наук, доц. каф. аерокосмічних радіоелектронних систем, Національний аерокосмічний університет ім. М. Є. Жуковського «Харківський авіаційний інститут», Харків, Україна.

Valeriy Volosyuk – D.Sc. in Radioengineering, Professor of Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: v.volosyuk@khai.edu, ORCID: 0000-0002-1442-6235.

Simeon Zhyla – PhD in Radioengineering, Head f Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: s.zhyla@khai.edu, ORCID: 0000-0003-2989-8988.

Vladimir Pavlikov – D.Sc. in Radioengineering, Vise rector for Science, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: v.pavlikov@khai.edu, ORCID: 0000-0002-6370-1758.

Dmitriy Vlasenko – Assistant of Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: d.vlasenko@khai.edu, ORCID: 0000-0002-6118-2173.

Vladimir Kosharskiy – Assistant of Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: v.kosharsky@khai.edu, ORCID: 0000-0002-8569-2047.

Denis Kolesnikov – Assistant of Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: d.kolesnikov@khai.edu, ORCID: 0000-0002-0135-2695.

Olga Inkarbaeva – Assistant of Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: o.inkarbayeva@khai.edu, ORCID: 0000-0002-2547-8241.

Kseniya Nezhalskaya – PhD in Radioengineering, Associate Professor f Department of Aerospace Radio-electronic Systems, National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine,
e-mail: kseniya.nezhalskaya@gmail.com, ORCID: 0000-0001-9349-8861.