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STATISTICAL SYNTHESIS OF AEROSPACE RADARS STRUCTURE WITH OPTIMAL SPATIO-TEMPORAL SIGNAL PROCESSING, EXTENDED OBSERVATION AREA AND HIGH SPATIAL RESOLUTION

Using the statistical theory of optimization of radio engineering systems the optimal method of coherent radar imaging of surfaces in airborne synthetic aperture radar with planar antenna arrays is developed. This method summarizes several modes of terrain observation and it is fully consistent with current trends in the development of cognitive radars with the possibilities of radiation pattern restructuring in space and adaptive reception of reflected signals. Possible modifications of the obtained optimal method for the operation of high-precision airborne radars with a wide swath are presented. ***The idea*** *is to create a theoretical basis and lay the foundations for its practical application in solving a wide range of issues of statistical optimization of methods and algorithms for optimal spatiotemporal signal processing in cognitive radar systems for the formation of both high-precision and global radar images. To implement the idea, the article highlights the concept of statistical optimization of spatio-temporal processing of electromagnetic fields in on-board cognitive radar systems, which will be based on the synthesis and analysis of methods, algorithms and structures of radar devices for coherent imaging, the study of limiting errors in restoring the spatial distribution of the complex scattering coefficient, the synthesis of optimal feedback for receiver and transmitter adaptations in accordance with a priori information about the parameters of the objects of study, the area of observation and the existing sources of interference.* ***Objective*** *is to develop the theory and fundamentals of the technical implementation of airborne radar systems for the formation of high-precision radar images in an extended field of view from aerospace carriers.* ***Tasks****. To reach the objective it is necessary to solve following tasks:*

– formalize mathematical models of spatiotemporal stochastic radio signals and develop likelihood functional for observation equations in which the useful signal, receiver internal noise and interference radiation of anthropogenic objects are random processes;

– to synthesize algorithms for optimal processing of spatio-temporal stochastic signals in multi-channel radar systems located on aerospace-based mobile platforms;

- in accordance with the synthesized methods, to substantiate the block diagrams of their implementation;

– obtain analytical expressions for the potential characteristics of the quality of radar imaging and determine the class of probing signals and space scanning methods necessary to perform various tasks of radar surveillance;

– to confirm some of the theoretical results by simulation methods, in which to reveal the features of the technical implementation of aerospace remote sensing radar systems.

Keywords: *cognitive radars; antenna array; statistical optimization; synthetic aperture radar.*

Introduction

Motivation. Earth remote sensing systems are used to solve many problems of the national economy. An important component of such systems is synthetic aperture radar (SAR) which makes it possible to obtain radar images of the Earth's surface with high spatial resolution, commensurate with optical images, in all weather conditions and regardless of the time of day.

State of the Art. Currently a significant number of high-precision satellite systems for remote sensing of the Earth have been developed. From the analysis of their

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technical characteristics follows that the spatial resolution of radar images is constantly improving. Despite significant results in the field of theory and practice of remote sensing [1, 2] and surfaces imaging [3] the problems of the synthesis of new methods and algorithms for estimating parameters and statistical characteristics of surfaces, the problems of developing high-precision structures of measuring systems with a spatial resolution of less than a decimeter and problems of experiments planning are still relevant.

In most cases, current trends in the development of remote methods for environmental media studies are aimed to improve secondary processing and increase the reliability of the interpretation of radar measurements. For example, one of the most up-to-date works of 2022 [4] is devoted to the development of quality indicator tools for multi-temporal DInSAR outputs, which are already generated and cannot be changed. Another work of 2020 [5] is devoted to the processing of Sentinel-1 raw data, which, according to the authors' opinion, can be considered as a milestone in the development of InSAR techniques. In addition to the development of raw data processing algorithms, it is also necessary to improve the methods for generating these raw data. Fairly recent work [6] also considers applications of the results of the SAR work and the PSInSAR technique to create a land subsidence inventory of the study area as a high-precision tool with a low cost and frequent reproducibility. To a lesser extent, the article touches upon the optimization of the system as a whole.

Works [7, 8] devoted to the optimization of radio systems are also of great importance for the future of space radio systems. At the same time the issues of end-to-end optimization of the spatio-temporal processing of the received field, starting from the moment of its registration, in these works are practically not considered. This fact does not allow to exceed the existing threshold of the accuracy and resolution. Usually the artificial aperture synthesis method is interpreted and investigated under the assumption that the radiation pattern of the airborne antenna is already set and the spatial processing of the received electromagnetic oscillations within the receiving aperture is completed. As a result of this simplification it is not possible to synthesize and analyze the optimal method for underlying surface observation and achieve the best spatial resolution of the radar images.

Methodology of research. To determine the optimal mode for underlying surface observation and achieve the best quality of radar imaging the generalized problem of synthesizing the optimal method of spatio-temporal processing of the electromagnetic field in aerospace-based radio engineering systems with planar antenna arrays has to be solved using modern results in the statistical theory of optimization active [9, 10], passive [11], single-channel [12] and multichannel [13] radio engineering systems.

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) collision warning radar for low-altitude safety (state registration number 0121U109598). These projects were obtained by the authors in the mentioned above institutions and were sponsored or would be sponsored by Ministry of education and science of Ukraine.

1. Geometry of the problem and model of the received signal

On the fig. 1 it is shown the geometry of surface sounding from the satellite. The flight altitude is indicated as H, and the speed is indicated as V. The movement of the aircraft is carried out along the axis x, in the XoZ plane. The parameters H and V are constant and are assumed to be known. On board of the spacecraft there is a phased antenna array with elements at points $\vec{r}' = (x', y', z') \in D'$. During the movement of the aircraft, the phase center of the antenna array has the following coordinates $(x' = Vt,\ y' = 0,\ z' = H)$ at each moment of time t.

It is assumed that for transmitting signals in the direction of the test surface D and to illuminate large surface area it is used group of dot radiators in the middle of the phased antenna array or one small antenna with a separate feeder. Transmitted signal $s_t(t)$ has the following form

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

In the (1) is used envelope of the probe signal $A(t)$, complex envelope $\dot{A}(t) = A(t)\exp(j\phi)$, initial phase ϕ, carrier frequency f_0, angular velocity $\omega_0 = 2\pi f_0$. In the general case $\dot{A}(t)$ represents a wide class of radio engineering signals.

The probing signal propagates into the area of surface irradiation D and irradiates each point, which is designated as $\vec{r} = (x, y, 0) \in D$. Due to the dielectric jump, each point of the surface reflects the probing signal. Scattered electromagnetic radiation is received by a phased antenna array at each point $\vec{r}' = (x', y', H) \in D'$. Each point of the receiving plane introduces changes in the phase and amplitude of the received field according to the law $\dot{I}(\vec{r}')$.

The received signal in each antenna of the receiving phased antenna array has the following form [14]:

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

Formula (2) introduces the function of the complex scattering coefficient $\dot{F}(\vec{r})$ of a small element $d\vec{r}$ on the surface D. The function $\dot{F}(\vec{r})$ will be subject to evaluation and is called a coherent image,

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

is the signal scattered by the element $d\vec{r}$ and received by each element of the phased antenna when $\dot{F}(\vec{r})=1$, $t_d(\vec{r},\vec{r}\,')$ is the time delay. In the literature the signal (3) is called a unit signal. The received signal model (2), being a special case of the Kirchhoff scalar formula, was studied in detail by the phenomenological approach in [14].

A unit signal (3) can be rewritten taking into account the geometry in Fig. 1

$$\dot{s}_0(t,\vec{r},\vec{r}\,') = \dot{S}_0(t,\vec{r},\vec{r}\,')\exp\left(j2\pi f_0 t\right), \qquad (4)$$

where

$$\begin{gathered}\dot{S}_0(t,\vec{r},\vec{r}\,') = \dot{I}(\vec{r}\,')\exp(j2k\vec{\vartheta}(\vec{r},t)\vec{r}\,')\times \\ \times\dot{A}(t-2R_0(\vec{r},t)c^{-1})\times \\ \times\exp(j2k(V(t-t_0)\cos\theta_x(\vec{r},t_0)))\times \\ \times\exp(-jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0))\ ),\end{gathered} \qquad (5)$$

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

is the vector of direction cosines, which varies in time and depends on the trajectory of the satellite, the distance from the middle of the antenna array to each point of the surface is denoted as $R_0(\vec{r},t)$.

2. Problem statement

According to the received signals $\dot{s}(t,\vec{r}\,')$ by each element of the antenna array D' and observed against the background of additive Gaussian noises $n(t,\vec{r}\,')$ it is necessary to optimally estimate the specific complex scattering coefficient $\dot{F}(\vec{r})$.

As the observation equations assumed an additive mixture of reflected useful signals and delta correlated internal noise of the receiving channels:

$$u(t,\vec{r}\,') = \mathrm{Re}\,\dot{s}(t,\vec{r}\,') + n(t,\vec{r}\,')\,. \qquad (6)$$

In formula (6) the white Gaussian noise is denoted by the function $n(t,\vec{r}\,')$, which has the correlation function

$$R_n(\tau,\Delta\vec{r}\,') = (N_0/2)\delta(t_1-t_2)\delta(\vec{r}_1\,'-\vec{r}_2\,')\,.$$

The elements of the antenna array have different amplitude-phase characteristics, but it is assumed that the energy level of the noise in each channel is the same and equal to N_0.

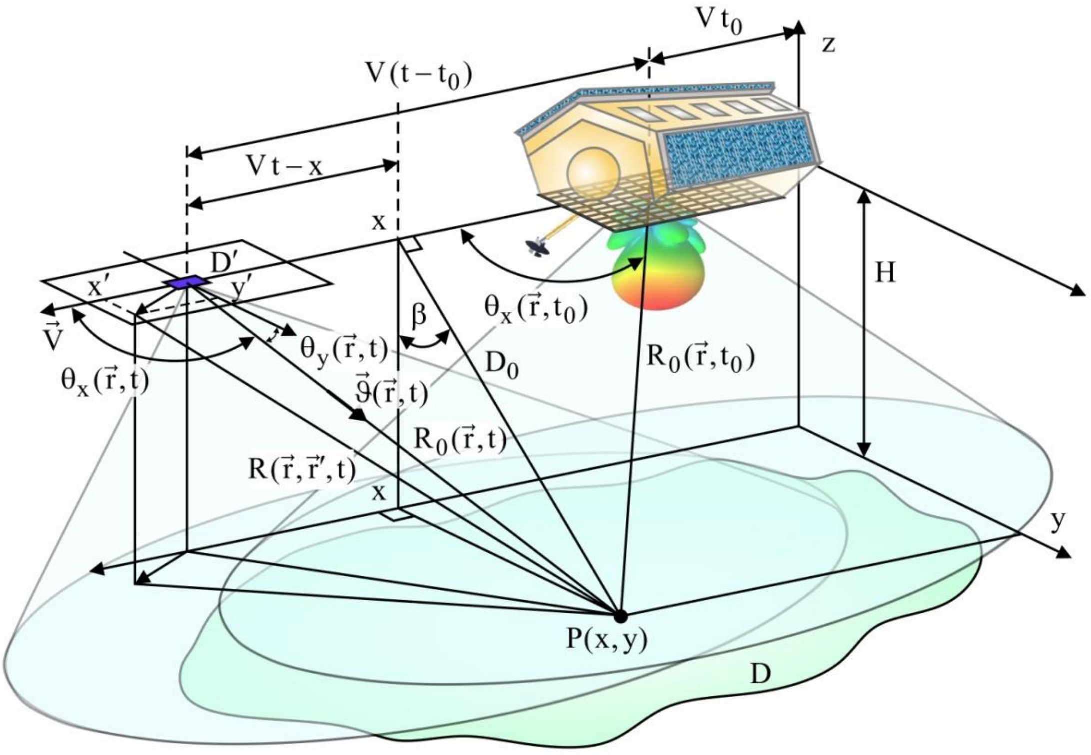


Fig. 1. Surface sensing geometry

3. Statistical optimization of the signal processing algorithm

We obtain the optimal method for estimating the parameters of the underlying surface by the maximum likelihood method. As shown in aerospace [15, 16] and ground [17, 18] researches, the likelihood functional for this problem can be written as follows

$$P[u(t,\vec{r}\,')\,|\,\dot{F}(\vec{r})] = \\ = \kappa\exp\{-N_0^{-1}\int_T\int_{D'}\left[u(t,\vec{r}\,') - \operatorname{Re}\dot{s}(t,\vec{r}\,')\right]^2 d\vec{r}\,'dt\}\,. \quad (7)$$

Formula (7) is used the parameter κ, which does not depend on the coherent image $\dot{F}(\vec{r})$, the observation time of scattered signals is denoted as T.

The maximum of functional (7) is found from the condition that its derivative with respect to the desired parameter $\dot{F}(\vec{r})$ be equal to zero. Because $\dot{F}(\vec{r})$ is a function of spatial coordinates, it is necessary to solve the problem with the variational derivative

$$\delta\ln P[u(t,\vec{r}\,')\,|\,\dot{F}(\vec{r})]/\delta\dot{F}(\vec{r})\Big|_{\dot{F}(\vec{r})=\hat{\dot{F}}_{opt}(\vec{r})} = 0\,, \quad (8)$$

$\delta/\delta\dot{F}(\vec{r})$ is the operator of the variational derivative with respect to the desired image.

The result of (8) is equation

$$2\int_T\int_{D'} u(t,\vec{r}\,')\dot{s}_0(t,\vec{r},\vec{r}\,')\,d\vec{r}\,'dt = \\ = \int_D \hat{\dot{F}}^*_{opt}(\vec{r}_1)\dot{\Psi}^*(\vec{r}_1,\vec{r})d\vec{r}_1\,, \quad (9)$$

where

$$\dot{\Psi}^*(\vec{r}_1,\vec{r}) = \int_T\int_{D'}\dot{S}_0^*(t,\vec{r}_1,\vec{r}\,')\dot{S}_0(t,\vec{r},\vec{r}\,')d\vec{r}\,'dt \quad (10)$$

is the ambiguity function of SAR.

The obtained form of the equation (9) is not simple and has already been interpreted in aerospace [15, 16] and ground [17, 18] researches. The left-hand side is the optimal signal processing method, and the right-hand side is the optimal radar image estimate $\hat{\dot{F}}_{opt}(\vec{r}_1)$ smoothed by the ambiguity function $\dot{\Psi}(\vec{r}_1,\vec{r})$.

Using the complex envelope method, we represent processing (9) as follows

$$\int_T\int_{D'}\dot{U}(t,\vec{r}\,')\dot{S}_0^*(t,\vec{r},\vec{r}\,')\,d\vec{r}\,'dt = \\ = \int_D \hat{\dot{F}}^*_{opt}(\vec{r}_1)\dot{\Psi}^*(\vec{r}_1,\vec{r})\,d\vec{r}_1, \quad (11)$$

where $\dot{U}(t,\vec{r}\,')$ is the complex envelope of the observation equation (6).

Substituting (5) into the left-hand side of (9), we obtain the optimal output effect in the aerospace radar system with a planar antenna array

$$\dot{Y}(\vec{r}) = \int_T\int_{D'}\dot{U}(t,\vec{r}\,')\dot{I}^*(\vec{r}\,')\exp(-j2k\vec{\vartheta}(\vec{r},t)\,\vec{r}\,')d\vec{r}\,'\times \\ \times\dot{A}^*(t-\frac{2R_0(\vec{r},t)}{c})\exp(-j\,2k\,(V(t-t_0)\cos\theta_x(\vec{r},t_0)))\times \\ \times\exp(j\,k\,(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)))dt. \quad (12)$$

4. Physical interpretation of the output effect

The essence of optimal spatio-temporal received field $\dot{U}(t,\vec{r}\,')$ processing according to (12) is as follows. At first, the antenna is focused on each point of the underlying surface $P(x,y)$. For this, the signals received at each point of the region D' with the coordinates $\vec{r}\,'$ are delayed for a time $\vec{\vartheta}(\vec{r},t)\,\vec{r}\,'c^{-1}$ and coherently added up with the amplitude-phase distribution $\dot{I}(\vec{r}\,')$. It should be noted that the delay in each channel at a time t_0 is made considering the vector $\vec{\vartheta}(\vec{r},t_0)$ of angles. This leads to the formation of a multi-beam pattern with the possibility of further processing of the signals for each beam separately.

The $\vec{\vartheta}(\vec{r},t)\,\vec{r}\,'c^{-1}$ multiplier shows that during the movement of the satellite in the antenna system such delays should be created that each radiation pattern should be focused on a selected point under the aircraft and change its angular position in time. Such operations overcome the inconsistency in synthetic aperture radars that high resolution cannot be obtained from large surfaces. The obtained field processing in the receiving area corresponds to the operation of a beam-forming circuit (BFC) with tunable delay lines, which lead to adaptive rotation of partial radiation patterns of the antenna array.

The next stage of processing is coherent amplitude detection, which can be implemented in serial or parallel circuits. Sequential processing consists in the convolution of signals at an intermediate frequency with an impulse response $\dot{A}^*(t-2R_0(\vec{r},t)c^{-1})$. Parallel processing involves the formation of a multi-channel scheme with multiple filters tuned to different ranges in each beam relative to distances $R_0(\vec{r},t)$. The separation between the filters is determined by the geometry of the problem and the correlation features of the envelope of the signals.

The multiplier $\exp(-j\,2k\,(V(t-t_0)\cos\theta_x(\vec{r},t_0)))$ characterizes the operation of Doppler frequency shift compensation.

The last exponent with a quadratic phase change reveals the essence of the classical method of aperture synthesis, which consists in the coherent accumulation of reflected signals along the flight path of the aircraft.

Signal processing accurate to the phase will make it possible to synthesize a new antenna aperture with large sizes. The length of the synthesized aperture is proportional to the speed of the aircraft and the accumulation time of the scattered signals. The accumulation time depends on the ability of the airborne radar to focus on a given area.

The described processing combines two methods of forming a synthesized aperture of the antenna in the case of Spotlight and Multi-view modes. At the same time, it implements the advantages of each of them. The obtained method has the highest spatial resolution in azimuth (along the flight path) due to the continuous focusing on the selected area and covers an extended observation area of the surface as a result of the formation of many partial antenna patterns.

The obtained generalized method can be used as the base structure for cognitive radars since it allows implement various modes of observation according to the task. In addition to the existing results, it is necessary to develop a method that is adaptive to the interference environment. This can be done by solving the problem under the assumption that the reflected signal is stochastic with the given correlation features.

The principle of the formation of the multiple antenna patterns followed by coherent processing of the trajectory signal is shown in Fig. 2. The projection of this figure onto a plane is shown in Fig. 3. The given sensing geometries show the process of continuous radar imaging of a surface with high spatial resolution without gaps.

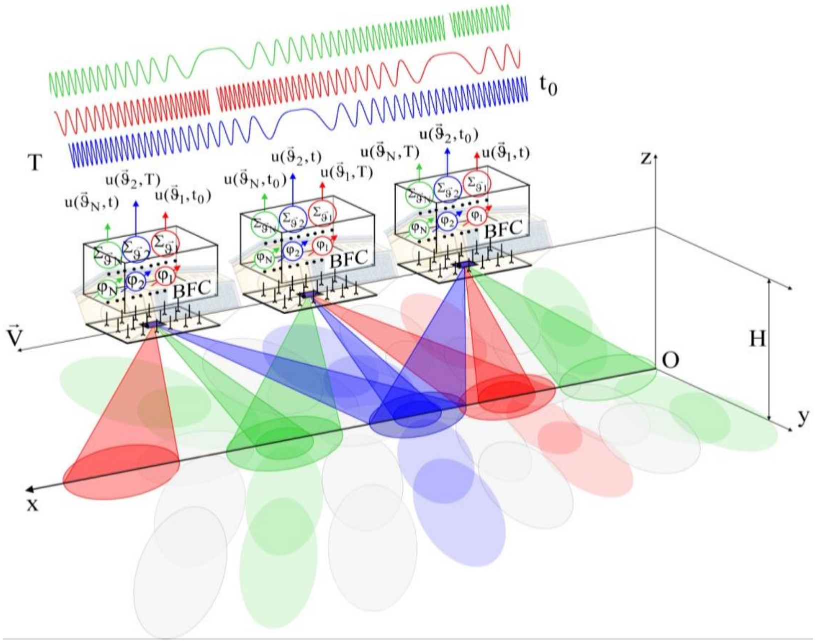


Fig. 2. The principle of the formation of a multiple radiation beams with coherent processing in each of them

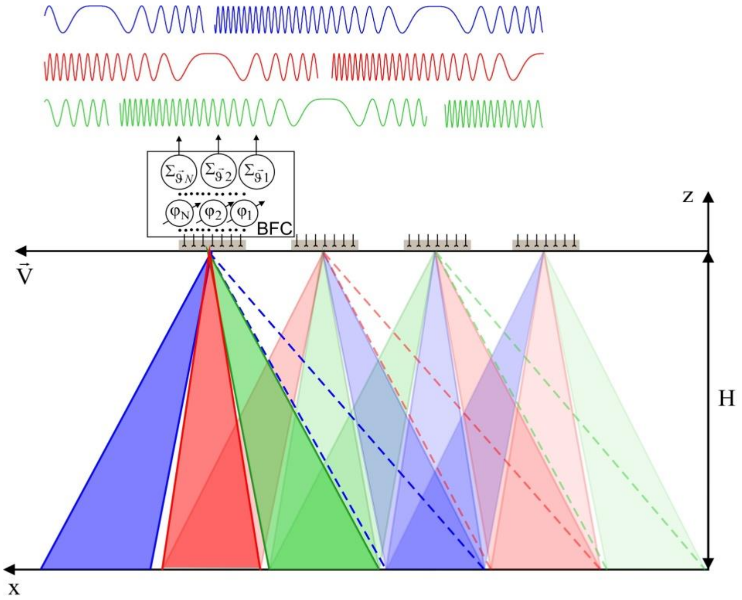


Fig. 3. Spatial accumulation of the trajectory signal during the Multi-view observation of the surface

5. Possible modification of the obtained optimal method

5.1. Multiple beam observation with fixed beams

It is of interest to investigate the method, which consists in the formation of a fixed fan of radiation patterns, the accumulation of sections of the chirp signal in each beam, the combination of the obtained sections, or the serial connection of the BFC outputs to the receiver and the matched processing of the trajectory signal in the form of convolution with a reference chirp signal. The effective width of each individual beam in the fan is determined by the linear dimensions of the antenna (D'_x, D'_y) and the amplitude-phase distribution $\dot{I}(\vec{r}')$. For an even distribution of amplitudes and a zero-phase distribution $\dot{I}(\vec{r}')=\mathrm{const}$ the effective beam width along the flight path will be $\Delta\theta_x \approx 0.88\lambda / D'_x$. The step between partial diagrams must be $\Delta\theta_x$ so the viewing angles of the selected surface point $P(x,y)$ "flow" continuously from one beam to another during the movement of the aircraft.

To obtain the analytical form of the proposed modification of the optimal method it is necessary to sample the observation time $(0,T)$ in such a way that the direction of each radiation pattern does not change. This kind of sampling is shown in Fig. 4.

Taking into account the discrete observation areas we write (12) in the following form:

$$\dot{Y}(\vec{r}) = \int_T \sum_{i=0}^{N-1} \Pi(t-iT_i)\,\dot{U}_i(t,\vec{r},i)\times$$
$$\times\dot{A}^*\Big(t-\frac{2R_0(\vec{r},i)}{c}\Big)\exp(-j2k(V(t-t_0)\cos\theta_x(\vec{r},t_0)))\times$$
$$\times\exp(jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)))dt, \quad (13)$$

where $\Pi(t-iT_i)$ is the sampling function.

5.2. Fixed fan of beams with coherent processing at the output of each channel and coherent inter-channel summation

To analyze this modification of the method, we rewrite expression (13) as follows

$$\dot{Y}(\vec{r}) = \sum_{i=0}^{N-1}\int_T \Pi(t-iT_i)\,\dot{U}_i(t,\vec{r},i)\,\dot{A}^*\Big(t-2\frac{R_0(\vec{r},i)}{c}\Big)\times$$
$$\times\exp(jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)))dt\times$$
$$\times\exp(-j2k(-V(t-t_0)\cos\theta_x(\vec{r},t_0))) =$$
$$=\sum_{i=0}^{N-1}\dot{Y}(\vec{r},i), \quad (14)$$

where

$$\dot{Y}(\vec{r},i) = \int_T \Pi(t-iT_i)\,\dot{U}_i(t,\vec{r},i)\,\dot{A}^*(t-2R_0(\vec{r},i)c^{-1})\times$$
$$\times\exp(-j2k(V(t-t_0)\cos\theta_x(\vec{r},t_0)))\times$$
$$\times\exp(jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)))dt \quad (15)$$

is the output effect for each antenna pattern.

The essence of method (15) is as follows:

1) registration of signals at the outputs of BFC $\dot{U}_i(t,\vec{r},i)$ and coherent detection of amplitudes $[\dot{U}_i(t,\vec{r},i)\,\dot{A}^*(t-2R_0(\vec{r},i)c^{-1})]$;

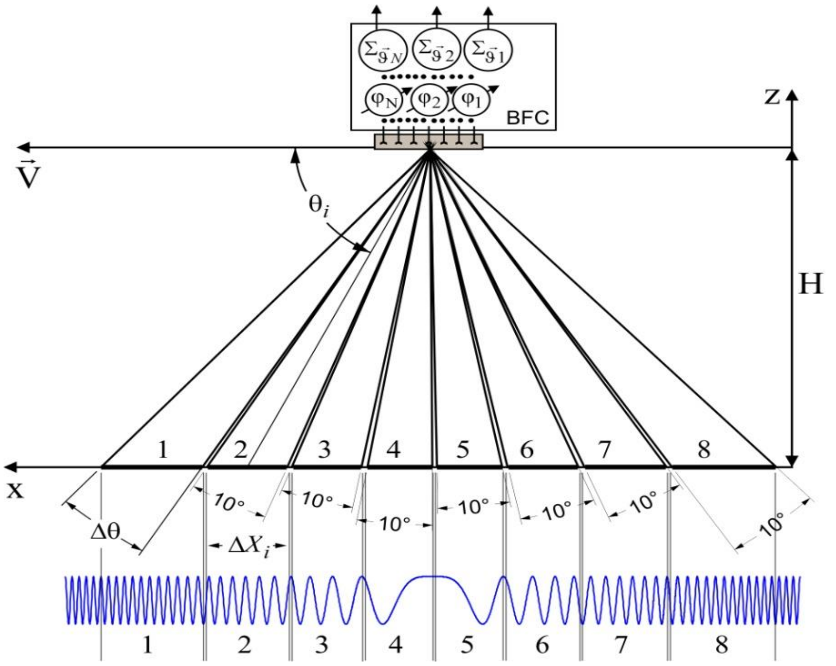


Fig. 4. Geometry of surface observation with a fixed fan of radiation patterns

2) the temporary separation of pulses into intervals that correspond to the observation of one surface area with different radiation patterns $\Pi(t-iT_i)[\dot{U}_i(t,\vec{r},i)\,\dot{A}^*(t-2R_0(\vec{r},i)c^{-1})]$;

3) the convolution of individual trajectory signals in different processing channels with the expected full reference signal

$$\exp\left(jk\left(\begin{array}{c}V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)-\\ -2V(t-t_0)\cos\theta_x(\vec{r},t_0)\end{array}\right)\right)$$

with duration T, which corresponds to the total time of sequential observation of one surface area with all directional patterns,

4) summing the results of the matched processing to form the final output effect $\dot{Y}(\vec{r})$.

The proposed modification of the algorithm also requires coherent summation and accurate phase tracking to obtain a synthesized radiation pattern. At the same time, separate preliminary processing of signals from different outputs of the BFC does not have strict requirements for overlapping and matching of antenna patterns, and also allows slight time offsets. So there is no need to form one continuous trajectory signal with exact transitions at the joints of diagrams.

5.3. Fixed fan of beams with coherent processing at the output of each channel and incoherent inter-channel summation

If it is not possible to achieve synchronization between signals from separate antenna patterns, i.e. it is not possible to coherently select parts of the trajectory signal by the function $\Pi(t-iT_i)$, then we can proceed to the method of incoherent averaging of output effects from various channels. For this it is necessary to limit the integration intervals in the method (15) and fix the point in each individual beam

$$\dot{Y}(\vec{r})=\sum\nolimits_{i=0}^{N-1}\int_{iT_i}^{(i+1)T_{i+1}}\dot{U}_i(t,\vec{r},i)\,\dot{A}^*(t-\frac{2R_0(\vec{r},i)}{c})\times$$
$$\times\exp[jk(V^2(t-t_{0i})^2R_0^{-1}(\vec{r},t_{0i})\sin^2\theta_x(\vec{r},t_{0i})-$$
$$-2V(t-t_{0i})\cos\theta_x(\vec{r},t_{0i})\,)]\,dt. \qquad (16)$$

According to the obtained analytical expression (16), the convolution will be performed only within the selected range of the beam pattern and subsequently participate in incoherent averaging with other beams with an index i. This method is already known and practically implemented. It has a resolution that is the same as for single-beam observation with StripMap mode, but is characterized by a reduced level of multiplicative noise (speckle noise) in the image due to incoherent averaging.

5.4. Fixed fan of beams with coherent signal processing at the output of each channel, compensation of the Doppler frequency shift and incoherent inter-channel summation

The above signal processing algorithms show the main optimal operations on the received oscillations and do not specify the type of the probing signal, the type of its modulation, coding, etc. At the same time, a significant part of existing SARs use a pulsed mode of operation and have in their processing algorithms a contradiction in the choice of pulse repetition rate: increasing the pulse repetition frequency allows increasing the SAR resolution in azimuth but leads to an ambiguous measurement of range. In this case, the algorithm presented in (16) on the extreme radiation patterns, at significant angles of deviation from the nadir, will be difficult to implement in practice. It is more expedient in each channel to compensate the Doppler frequency shift due to the deviation of the i-th radiation pattern by an angle and then perform coordinated processing with the reference signal at a lower frequency. As a result it is necessary to present (16) in the following form:

$$\dot{Y}(\vec{r})=\sum\nolimits_{i=0}^{N-1}\int_{iT_i}^{(i+1)T_{i+1}}[\,\dot{U}_i(t,\vec{r},i)\,\times$$
$$\times\exp(-j2\pi(2V\cos\theta_x(\vec{r},t_{0i}))\lambda^{-1}(t-t_{0i}))\times$$
$$\times\dot{A}^*(t-2R_0(\vec{r},i)c^{-1})\times$$
$$\times\exp(jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_{0i})\sin^2\theta_x(\vec{r},t_{0i})))dt. \quad (17)$$

Compensation of the Doppler frequency shift of the trajectory signal before the coordinated processing allows using the same pulse repetition rate in each channel and, in the general case, reducing its value to achieve unambiguous range measurements.

5.5. Single beam SAR

Further simplifications of expression (17) can lead to well-known SAR imaging modes. Assuming one beam and many range channels, we obtain a generalized SAR for anterolateral, strictly lateral and posterolateral Stripmap SAR

$$\dot{Y}(\vec{r})=\int_0^T\dot{U}_i(t,\vec{r})\exp(-j4\pi(\frac{V\cos\theta_x(\vec{r},t_0))}{\lambda}(t-t_0))\times$$
$$\times\dot{A}^*(t-2R_0(\vec{r})c^{-1})\times$$
$$\times\exp(jk(V^2(t-t_0)^2R_0^{-1}(\vec{r},t_0)\sin^2\theta_x(\vec{r},t_0)))dt. \quad (18)$$

6. Simulation result

Analysis of algorithm (12) shows that operation of multiple beams forming is very important for SAR imaging, because it not only increases scene size, but also gives new information about man-made objects. To such objects can be attributed buildings with metal roof, aircrafts, ships and any other objects with smooth surfaces and large roughness compare to operating wavelength. In work [3] it is mentioned that AER-II image with one-meter resolution, PAMIR image with 20cm resolution are less informative than aerial optical image with 30cm resolution (Fig. 5). Such effect of invisibility occurs because the incident angle of transmitted electromagnetic waves does not equal to specular angle. In this part we propose to simulate different surfaces and calculate areas that can be retrieved with SAR.

Using the computing environment MATLAB the test model of the surface with manmade objects was developed taking into account the phenomenological description of the electromagnetic field and coherent images [14]. The model of elevation for whole surface is shown in the Fig 6, a-b and for manmade objects in the Fig 6, c-d and Fig 7, a-d. The radar cross section $\sigma^0(\vec{r})$ and real part of the complex scattering coefficient $\dot{F}(\vec{r})$ for each point of the test surface are shown in the Fig 8.

To verify the simulation at first the optimal output effect $\left|\dot{E}(x,y)\right|$ in the aerospace radar system (12) was obtained for one beam with the following parameters: $\theta_x(\vec{r},t)=0$, $\theta_y(\vec{r},t)=0$, $f_0=10\text{ GHz}$, $H=10\text{ km}$, surface dimension $150\,\text{m}\times150\,\text{m}$, ambiguity function size $3\text{m}\times3\text{m}$ and $1\text{m}\times1\text{m}$. The radar images for these parameters are depicted in the Fig 8, a-d.

For more practical results was simulated radar images with the same parameters but for observation with one beam ($\theta_x(\vec{r},t)=90°$ $\theta_y(\vec{r},t)=(20°\div20.5°)$), incoherent summation of two beams ($\theta_x(\vec{r},t)=(90°,60°)$, $\theta_y(\vec{r},t)=(20°\div20.5°)$), incoherent summation of three beams ($\theta_x(\vec{r},t)=(90°, 60°, 120°)$, $\theta_y(\vec{r},t)=(20°\div20.5°)$) and coherent summation in three beams Spotlight mode (optimal mode). All simulated images are shown in the Fig. 9.

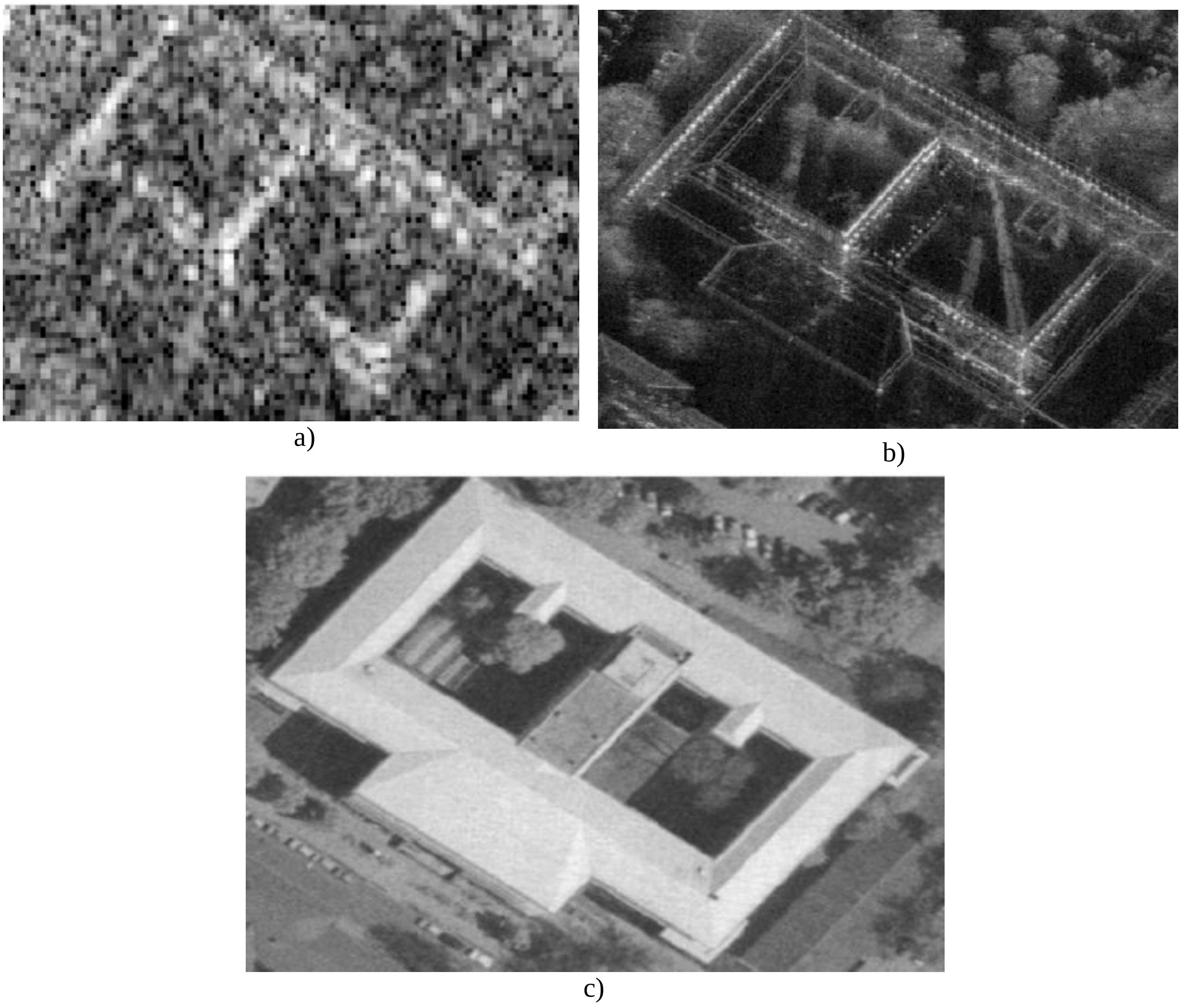


Fig. 5. Images with different resolution: a) AER-II image with one-meter resolution; b) PAMIR image with resolution 20 cm; c) Aerial optical image with resolution 30cm

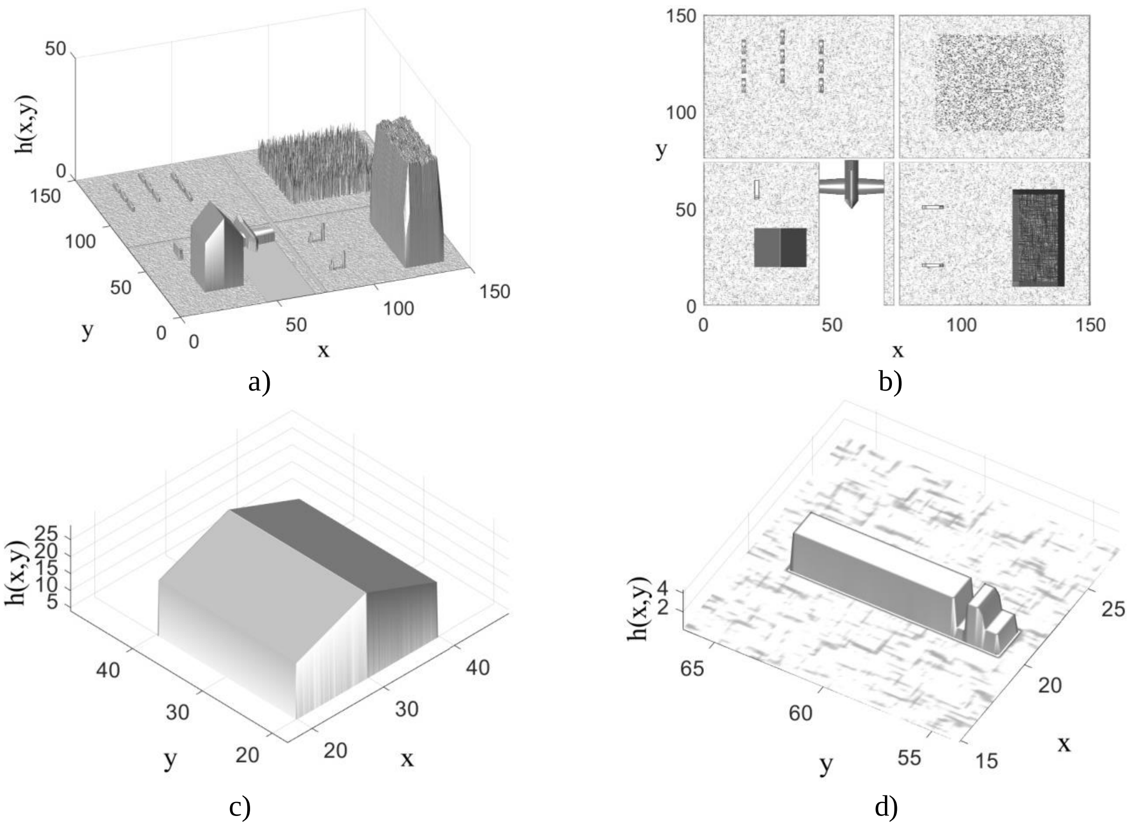


Fig. 6. The elevation models: a) whole surface; b) Top view of the surface; c) building; d) truck

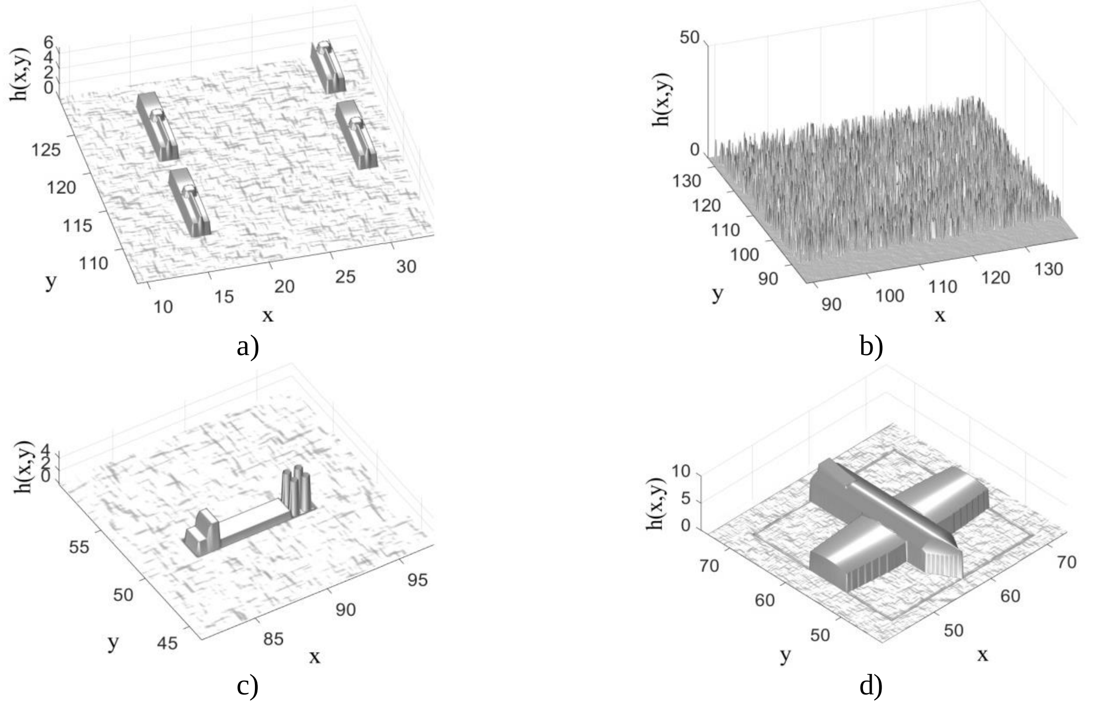
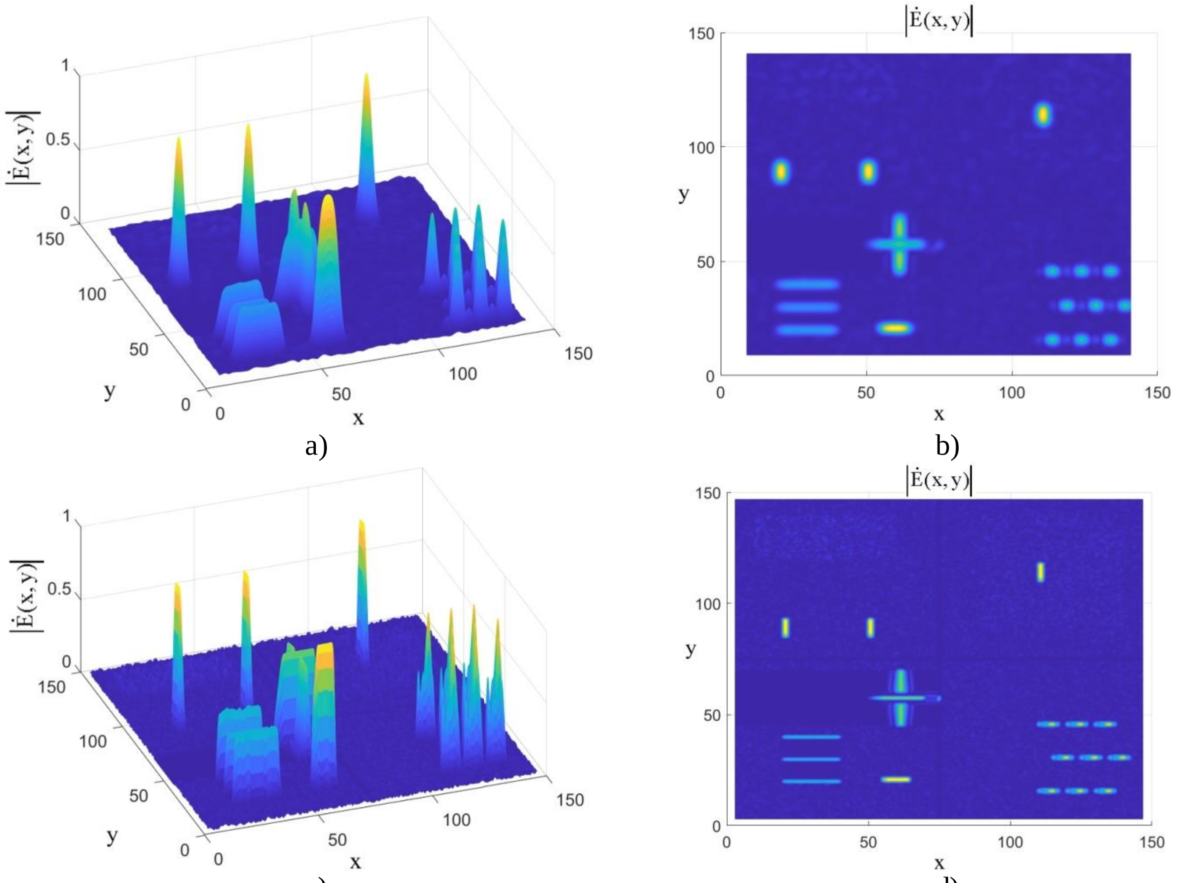


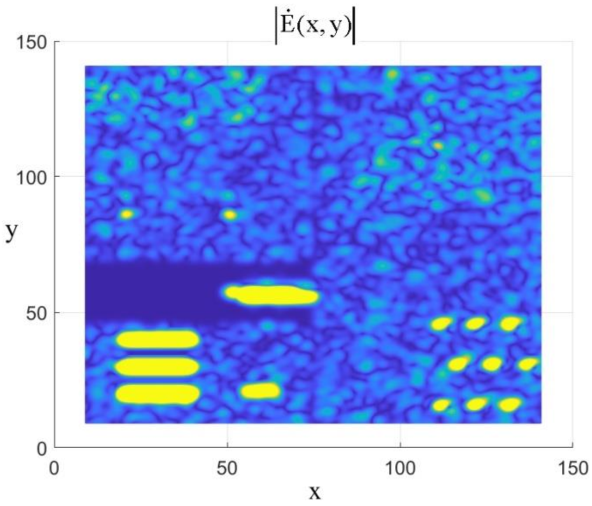
Fig. 7. The elevation models: a) tanks; b) forest; c) mobile surface-to-air missile system; d) aircraft



a) b)

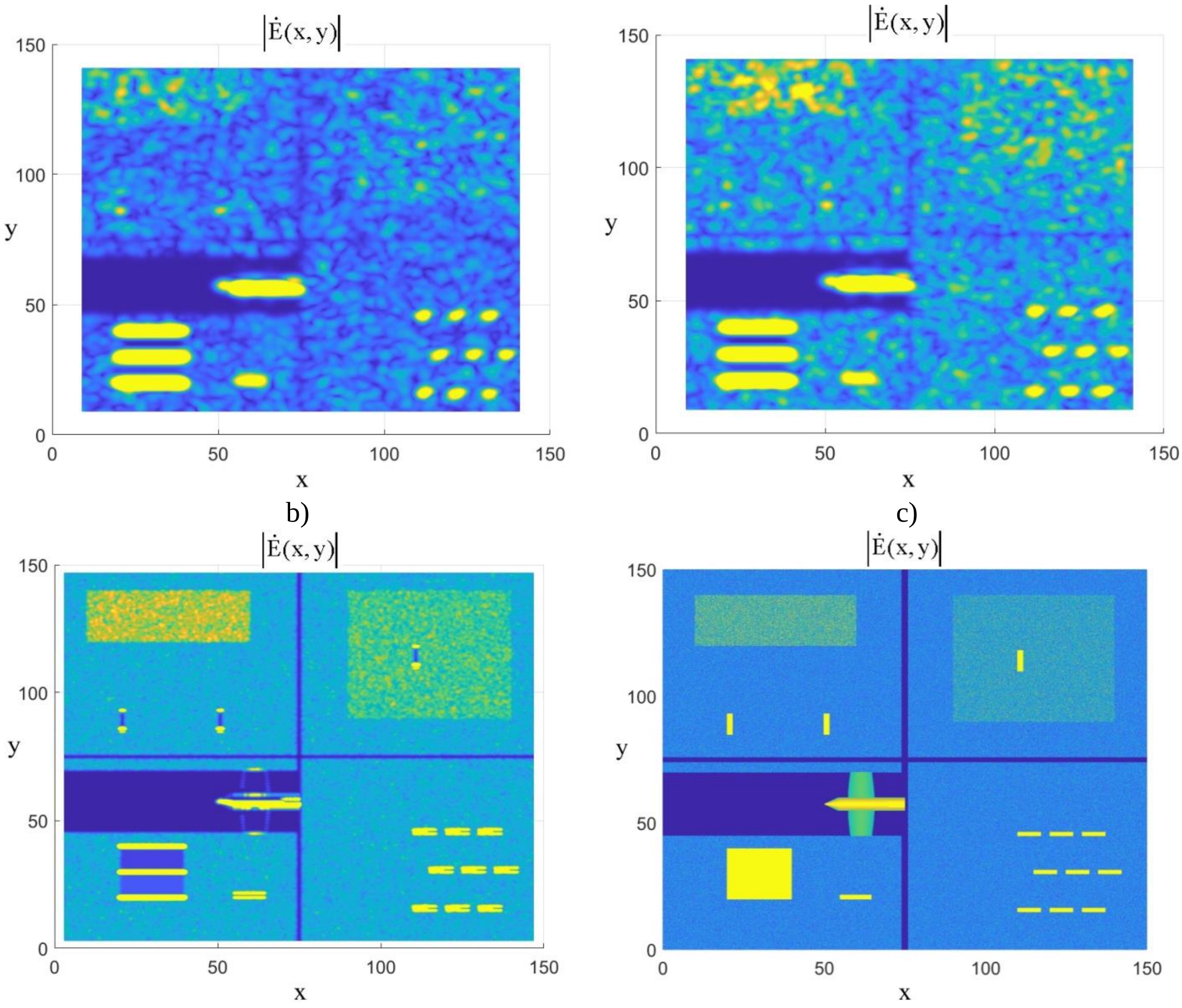
c) d)

Fig. 8. Output effect $|\dot{E}(x,y)|$ in the aerospace radar system: a) ambiguity function size $3\text{m}\times3\text{m}$; b) top view of $|\dot{E}(x,y)|$ when ambiguity function size is $3\text{m}\times3\text{m}$; c) ambiguity function size $1\text{m}\times1\text{m}$; d) top view of $|\dot{E}(x,y)|$ when ambiguity function size is $1\text{m}\times1\text{m}$



a)

Fig. 9. Modulus and output effect $|\dot{E}(x,y)|$ in the aerospace radar system: a) Modulus of the ideal complex scattering coefficient; b) Observation with one beam; c) Incoherent summation of two beams



b) c) d) e)

Fig. 9. Modulus and output effect $|\dot{E}(x,y)|$ in the aerospace radar system: b) Observation with one beam; c) Incoherent summation of two beams; d) Incoherent summation of three beams; e) Coherent summation in three beams Spotlight mode (optimal output effect)

For obtained radar images on the Fig. 9 it was calculated their entropy, quality and distinction from the test image with the full-reference [19, 20] and no-reference quality metrics [21]: Mean-squared error (MSE), Peak signal-to-noise ratio (pSNR), Structural similarity (SSIM) index, Blind/Referenceless image spatial quality evaluator (BRISQUE), Natural image quality evaluator (NIQE) and Perception based Image quality evaluator (PIQE). All results are summarized in the Table 1.

According to full-reference metrics (MSE, pSNR, SSIM) optimal output effect is not always the best, because images dynamic range was adjusted manually. In practice in order to see the structure of the image in the presence of powerful reflectors the dynamic range is also adjusted during the secondary processing of radar images. In contrast all the no-reference metrics (BRISQUE, NIQE, PIQE) shows the best quality for optimal output effect, it is even better than reference image.

Table 1

Comparison of the simulated and test radar images

Figure	MSE	pSNR	SSIM	BRISQUE	NIQE	PIQE
Fig. 11,a	0	Inf	1	43.0494	8.5282	69.4806
Fig. 11,b	0.0384	14.1592	0.1939	57.4215	9.2167	84.3591
Fig. 11,c	**0.0349**	14.5726	0.2046	56.2384	8.9705	82.8793
Fig. 11,d	0.0544	12.6468	**0.1925**	56.6353	8.7231	83.2645
Fig. 11,e	0.0650	**11.8705**	0.2116	**46.8832**	**5.9386**	**46.6039**

It is because the modulus of the ideal complex scattering coefficient is very stochastic and restored radar images are smoothed by the ambiguity function.

From the obtained results it follows that proposed optimal method of imaging in the aerospace radar system with a planar antenna array is more informative, gives results without gaps and has the highest spatial resolution in azimuth coordinate.

Conclusions

From the solution of the optimization problem the optimal method for signals processing in SAR with a planar antenna array is obtained. This method combines the advantages of multi-look and SpotLight modes of surface observation. For the implementation of cognitive radars, it is necessary to have several modes of high-precision radar imaging in advance, which can be obtained from the above method by introducing the necessary restrictions. The obtained optimal analytical expressions are rather difficult to implement with a modern element base, therefore reducing the quality of radar images the expressions for quasi-optimal methods are shown. All results are fundamental and physical, since on the one hand they show potential the capability of the aerospace radar system with a planar antenna array, and on the other hand, in particular cases, the solutions correspond to already known results.

According to the scales of the mentioned in introduction R&D projects the obtained results develop the statistical theory for the synthesis of optimal methods for spatio-temporal processing of functionally determined signals in multi-channel cognitive radio-vision radar systems. In particular, models of spatio-temporal functionally determined signals are mathematically formalized, methods for optimal spatio-temporal processing of functionally deterministic signals are synthesized and investigated and errors of radar imaging are investigated.

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СТАТИСТИЧНИЙ СИНТЕЗ СТРУКТУРИ АЕРОКОСМІЧНИХ РАДІОЛОКАТОРІВ З ОПТИМАЛЬНОЮ ПРОСТОРОВО-ЧАСОВОЮ ОБРОБКОЮ СИГНАЛІВ, РОЗШИРЕНОЮ ЗОНОЮ СПОСТЕРЕЖЕННЯ І ВИСОКОЮ ПРОСТОРОВОЮ РОЗДІЛЬНОЮ ЗДАТНІСТЮ

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З використанням статистичної теорії оптимізації радіотехнічних систем розроблено оптимальний метод когерентного формування радіолокаційного зображення поверхонь в бортовій радіолокаційній системі з синтезованою апертурою і планарними антенними решітками. Цей метод узагальнює кілька режимів спостереження за місцевістю та повністю відповідає сучасним тенденціям створення когнітивних радіолокаторів з можливістю перебудови діаграми спрямованості у просторі та адаптивного прийому відбитих сигналів. Представлені можливі модифікації отриманого оптимального методу роботи високоточних бортових радіолокаторів з широкою смугою огляду.

Ідея полягає в тому, щоб створити теоретичну базу та закласти основи для її практичного застосування при вирішенні широкого кола питань статистичної оптимізації методів та алгоритмів оптимальної просторово-часової обробки сигналів у когнітивних радіолокаційних системах для формування як високоточних, так і глобальних радіозображень місцевості. Для реалізації ідеї в статті висвітлено концепцію статистичної оптимізації просторово-часової обробки електромагнітних полів у бортових когнітивних радіолокаційних системах, яка ґрунтуватиметься на синтезі та аналізі методів, алгоритмів і структур радіолокаційних пристроїв когерентної візуалізації, дослідження граничних похибок відновлення просторового розподілу зворотного зв'язку для адаптації приймача та передавача відповідно до апріорної інформації про параметри об'єктів дослідження, району спостереження та наявні джерела перешкод.

Мета – розробка теорії та основ технічної реалізації бортових радіолокаційних систем формування високоточного радіолокаційного зображення у розширеному полі зору з аерокосмічних носіїв.

Завдання. Для досягнення поставленої мети необхідно вирішити такі завдання:

– формалізувати математичні моделі просторово-часових стохастичних радіосигналів та розробити функціонал правдоподібності для рівнянь спостереження, в яких корисний сигнал, внутрішні шуми приймача та перешкодове випромінювання техногенних об'єктів є випадковими процесами;

– синтезувати алгоритми оптимальної обробки просторово-часових стохастичних сигналів у багатоканальних радіолокаційних комплексах, що розміщуються на мобільних платформах аерокосмічного базування;

– відповідно до синтезованих методів обґрунтувати блок-схеми їх реалізації;

– отримати аналітичні вирази для потенційних характеристик якості радіолокаційної зйомки та визначити клас зондувальних сигналів та методи сканування простору, необхідні для вирішення різних завдань радіолокаційної розвідки;

– підтвердити деякі теоретичні результати методами імітаційного моделювання, у яких виявити особливості технічної реалізації аерокосмічних радіолокаційних систем дистанційного зондування.

Ключові слова: когнітивні радари; антенна решітка; статистична оптимізація; радар із синтезованою апертурою.

СТАТИСТИЧЕСКИЙ СИНТЕЗ СТРУКТУРЫ АЭРОКОСМИЧЕСКИХ РАДИОЛОКАТОРОВ С ОПТИМАЛЬНОЙ ПРОСТРАНСТВЕННО-ВРЕМЕННОЙ ОБРАБОТКОЙ СИГНАЛОВ, РАСШИРЕННОЙ ЗОНОЙ НАБЛЮДЕНИЯ И ВЫСОКИМ ПРОСТРАНСТВЕННЫМ РАЗРЕШЕНИЕМ

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С использованием статистической теории оптимизации радиотехнических систем разработан оптимальный метод когерентного формирования радиолокационного изображения поверхностей в бортовой радиолокационной системе с синтезированной апертурой и планарными антенными решетками. Этот метод обобщает несколько режимов наблюдения за местностью и полностью соответствует современным тенденциям создания когнитивных радиолокаторов с возможностью перестройки диаграммы направленности в пространстве и адаптивного приема отраженных сигналов. Представлены возможные модификации полученного оптимального метода для работы высокоточных бортовых радиолокаторов с широкой полосой обзора.

Идея состоит в том, чтобы создать теоретическую базу и заложить основы для ее практического применения при решении широкого круга вопросов статистической оптимизации методов и алгоритмов оптимальной пространственно-временной обработки сигналов в когнитивных радиолокационных системах для формирования как высокоточных, так и глобальных радиоизображений местности. Для реализации идеи в статье освещена концепция статистической оптимизации пространственно-временной обработки электромагнитных полей в бортовых когнитивных радиолокационных системах, которая будет основываться на синтезе и анализе методов, алгоритмов и структур радиолокационных устройств когерентной визуализации, исследование предельных погрешностей восстановления пространственного распределения комплексного коэффициента рассеяния, синтез оптимальной обратной связи для адаптации приемника и передатчика в соответствии с априорной информацией о параметрах объектов исследования, района наблюдения и существующей источники помех.

Цель - разработка теории и основ технической реализации бортовых радиолокационных систем формирования высокоточного радиолокационного изображения в расширенном поле зрения с аэрокосмических носителей.

Задания. Для достижения поставленной цели необходимо решить следующие задачи:

– формализовать математические модели пространственно-временных стохастических радиосигналов и разработать функционал правдоподобия для уравнений наблюдения, в которых полезный сигнал, внутренние шумы приемника и помеховое излучение техногенных объектов являются случайными процессами;

– синтезировать алгоритмы оптимальной обработки пространственно-временных стохастических сигналов в многоканальных радиолокационных комплексах, размещаемых на мобильных платформах аэрокосмического базирования;

– в соответствии с синтезированными методами обосновать блок-схемы их реализации;

– получить аналитические выражения для потенциальных характеристик качества радиолокационной съемки и определить класс зондирующих сигналов и методы сканирования пространства, необходимые для решения различных задач радиолокационной разведки;

– подтвердить некоторые теоретические результаты методами имитационного моделирования, в которых выявить особенности технической реализации аэрокосмических радиолокационных систем дистанционного зондирования.

Ключевые слова: когнитивные радары; антенная решетка; статистическая оптимизация; радар с синтезированной апертурой.

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