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Radar Information Processing Algorithms in a Specialized Computer-Aided Design System

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Abstract: **A brief description of the radar CAD software modules responsible for this functionality is given. The module of engineering calculations and simulations allows you to set the scenario of the interference-target situation and conduct a complete, close to reality, simulation of the behavior of the radar in combat conditions. The visual functional editor provides the ability to create a radar simulation model in the form of a graph of streaming calculations from interconnected parameterizable blocks. The library of parameterizable modeling blocks contains modeling blocks designed for calculations and modeling of structural and functional parts of developed radar stations, complexes, systems. Simulation model of an active single-position pulse-Doppler sector-observation radar with electronic beam scanning was created. The following algorithms are implemented in the model: the sum-difference monopulse direction finding algorithm, the MUSIC superresolution direction finding algorithm, and the projection adaptive spatial filtering algorithm. A simulation experiment was carried out with a radar model in three scenarios of an interference-target environment, which differ in the presence of interfering signals. Analysis of the results of the simulation experiment shows that the operation of the algorithms corresponds to the theoretical prediction. The abilities of radar CAD presented in this article can be used by specialists in radar and signal processing.**

Keywords: **radar station, computer-aided design system, simulation modeling, radar data processing algorithm**

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Contents

1. INTRODUCTION

The most part of tasks for performance evaluation of the combat use of various equipment in the aerospace defense system are complex and cannot be reduced to a simple arithmetic sum of mathematical models that are poorly interconnected and tasks for calculating particular indicators. The current level of development of computer technology and mathematical methods for studying complex systems creates objective prerequisites for the system concept of designing complex technical systems, which requires fundamental changes in the methodology of their creation and development. The system approach involves the creation of effective complexes of particular mathematical models of subsystems, which together describe the behavior of the entire system, and computational tasks that function as part of modeling and design systems on a unified information base [1,2].

The computer-aided design system (CAD) for radars, radar complexes and radar systems, as well as their components, is an example of the implementation of the system concept [3-10]. The systematic nature of the calculations in the radar CAD implies:

- a unified methodology for preparing and presenting initial data, as well as calculating and presenting results;
- an equal degree of detail for each particular task (model) solved by users of the same level;
- a specific logical sequence of calculations in each particular task and in their totality;
- obtaining both intermediate and final results for each calculation task in a form convenient for their application in other tasks without additional processing and transformation;
- the possibility of independent calculations for each calculation problem, mathematical model and the use of intermediate and final results in other tasks.

The systematic approach implemented in the radar CAD provides for the unity of information, mathematical, linguistic, software and organizational support.

From the standpoint of a systematic approach, simulation models are the most proper for performance evaluation of complex systems. Therefore, as part of the radar CAD, simulation models of the functioning of the radar have been developed, which, unlike many of the currently existing mathematical models of the radar, make it possible to model in detail the processes of primary and secondary processing of various types of signals reflected from air, ballistic and space objects in a full polarization basis.

This article is devoted to an overview and demonstration of the capabilities of radar CAD in terms of developing and modeling algorithms for processing radar information. The article addresses the following questions:

- description of radar CAD tools, including module of engineering calculation and simulation, visual functional editor and library of parameterizable simulation blocks;
- outlined the principles of assembling simulation models of the radar;
- test simulation of the radar model and its algorithms is described;
- a simulation experiment was carried out, its results are presented.

2. RADAR CAD TOOLKIT

2.1. Module of engineering calculation and simulation

One of the key features of the developed radar CAD is the possibility of not only automating the radar development process, but also a fairly wide and comprehensive modeling of the behavior of the radar in combat conditions. In particular, when designing, the engineer is given the opportunity to set a scenario. When sending the scenario for calculation, a complete, close to reality, simulation of the behavior of the radar in combat conditions is performed. An imitation of a raid on a radar station is carried out, which includes the simulation of the movement of various air targets. At the same time, on the basis of the constructed radar model, the operation of the radar antenna is modeled, it scans the space. During the interaction of an electromagnetic wave that came from the locator antenna beam and an air target, the reflection of an electromagnetic wave from this target is simulated, on the basis of which the signal that came into the receiving channel of the locator is calculated, where, further, its processing is simulated. Noises are superimposed on the incoming signal, which arise, among other things, due to reflection from the Earth's surface. Also, when modeling the transition of a beam through the atmosphere, various kinds of precipitation are taken into account.

The interface of the module of engineering calculations and modeling that implements these capabilities is shown in **Fig. 1**.

During the simulation, a file of the protocol of the simulation experiment is recorded, containing information about the position of all radars and air targets presented in the scenario, and the results of the radar operation. As a result of processing the simulation protocol file in the performance evaluation module, the quality indicators of radar information received from the radar are calculated.

2.2. Visual functional editor

In radar CAD, to create simulation models, an approach known as "dataflows programming" is used [11]. Popular representatives of software tools using this approach are Simulink and LabView.

The user, using the visual constructor, creates a calculation graph from blocks, configures the parameters of each block and the connections between them. By pressing the start calculation button, the graph is traversed and the output data of each block is calculated based on the input data and block parameters.

The advantages of this paradigm are a natural visual representation (in the form of a calculation graph) and support for parallelism.

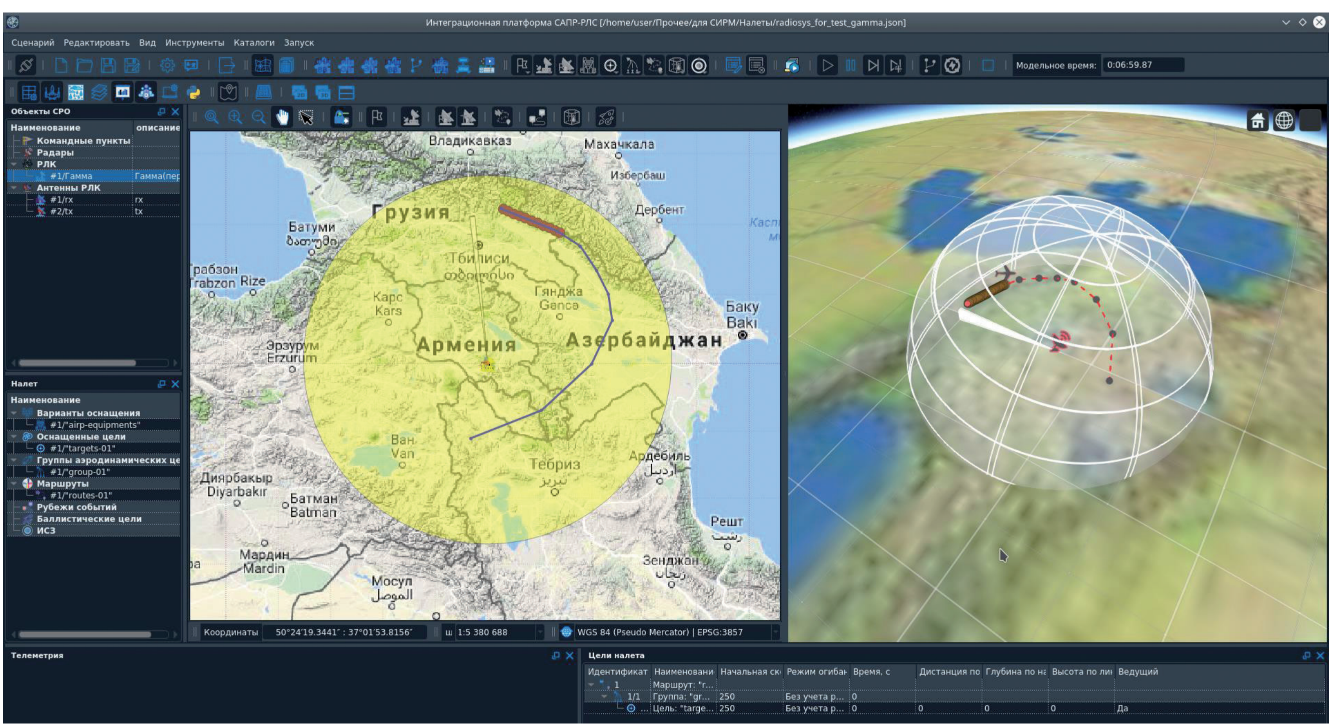

Fig. 1. *The interface of the module of engineering calculation and simulation.*

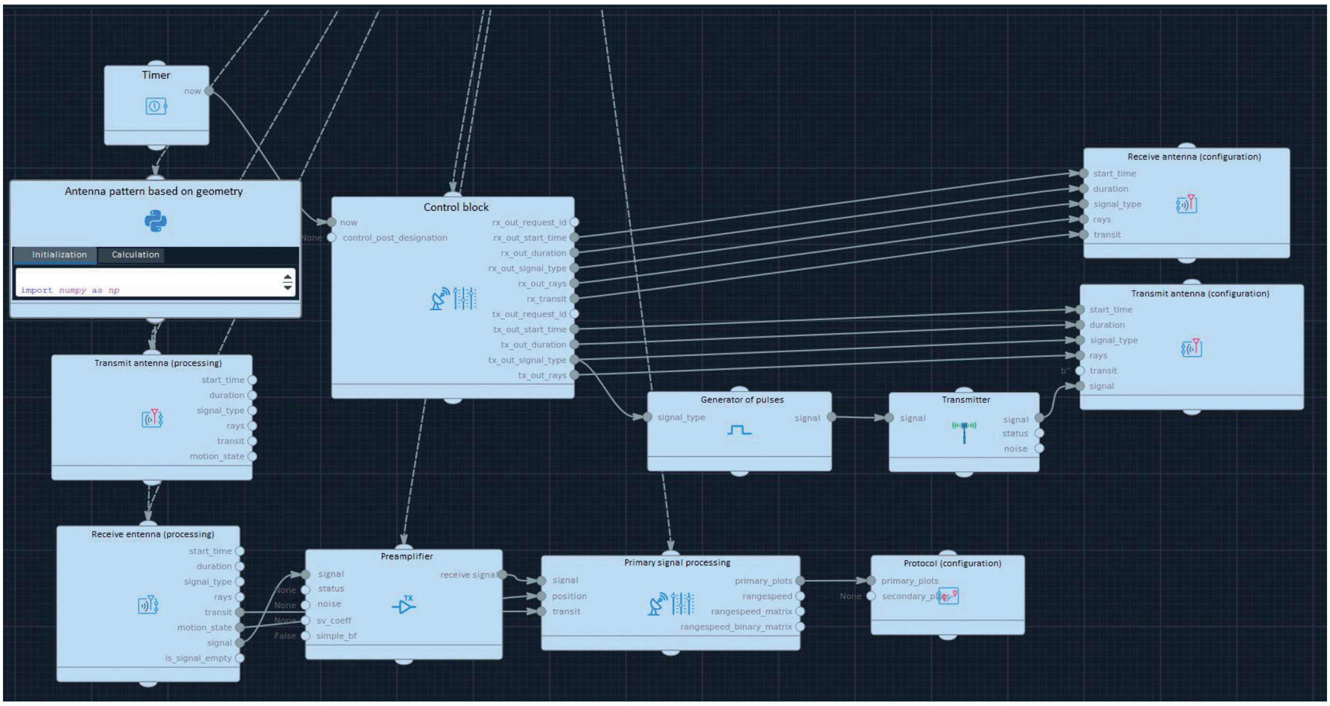

Fig. 2. *A typical scheme of the radar model.*

A visual functional editor has been developed as part of the radar CAD, which provides the ability to create and calculate a data-flow graph. The graphical user interface is a classic Simulink-like interface for visual design of stream data processing, consisting of parameterizable interconnected blocks (**Fig. 2**).

2.3. Library of parameterizable simulation blocks

When modeling a radar, two levels of abstraction can be distinguished: the lower one, that is, the modeling of particular modules and units (generators, antennas, algorithmic blocks, etc.) and the upper one, that is, the model of the system as a whole. At the same time, if the principle of modularity is kept, then the same set of components can be used to simulate various types and configurations of radars.

In addition, if the program code responsible for the internal operation of particular modules is placed in a separate well-debugged and documented library, then the development of the upper level of abstraction can be highly simplified: the developer of a particular simulation model will need to go into the details of mathematically complex signal processing algorithms inside individual modules.

To do this, the functional editor includes a library of parameterizable simulation blocks designed for calculations and modeling of the structural and functional parts of the developed radar stations, complexes, systems. The library includes a basic set of blocks that represents an opportunity to create a radar model.

2.4. Radar simulation model

The main object in simulation modeling is the simulation model of the radar. The radar simulation model in the radar CAD is represented as a set of functional blocks. A typical radar model consists of the following functional blocks:

- generator of radar signals;
- transmitter;
- transmitting antenna;
- receiving antenna;
- beamformer;
- receiver;
- digital signal processing block;
- primary information processing block;
- secondary information processing block;
- operating mode control block.

As seen, the accepted division of the model into blocks corresponds to the classical functional scheme of the radar, known from the literature [12]. At the same time, the open architecture of radar CAD does not impose restrictions on the user - the configuration of blocks in the model can be arbitrary. New blocks that have the functionality necessary for the user can be developed in the programming languages Python, MATLAB and C ++.

3. SIMULATION EXPERIMENT

3.1. Radar simulation model parameters

To demonstrate the capabilities of radar CAD in terms of developing and modeling processing radar information algorithms, an airspace surveillance radar simulation model with a set of parameters typical for this class was created [12].

Radar type - active, single-position, sector surveillance with electronic beam scanning.

Signal parameters:

- signal type – chirp;
- carrier frequency = 1.2 GHz;
- signal bandwidth = 1 MHz;
- pulse duration = 200 μs;
- pulse repetition period = 2 ms;
- pulse power = 20 kW.

Antenna parameters:

- type of antenna - digital antenna array (DAA);
- size in elements = 12x16;
- step of elements = 0.5 wavelength;
- gain factor = 28 dB;
- scanning sector in azimuth = -45° – 45°;
- scanning sector in elevation = 0° – 30°;
- antenna tilt to the horizon = 15°.

4. RADAR SIMULATION ALGORITHMS

The radar simulation model implements a typical signal generation and processing scheme for a pulse-Doppler radar, which looks like this:

- generation of a chirp signal;
- calculation of the phase distribution for beamforming;
- filtering the received signal by range using a matched filter;
- short-time Fourier transform for a range-velocity matrix;
- binarization of the range-velocity matrix using a detector with a constant false alarm rate;
- search connected regions of the binary range-velocity matrix;
- reproduction of connected regions for other ranges and speeds for a specific pulse burst;
- search for intersections between multiplied connected regions obtained from different bursts;
- for those regions that intersect with a sufficient number of regions from other bursts (for example, in the case of intersection of regions from three different pulse bursts), the indicators are averaged and a target mark is issued.

In addition, a passive channel is implemented in the radar model, which implements the processing of stochastic signals from external sources. In this case, training data with a DAA of length K = 384 time samples are used.

To illustrate the capabilities of the radar CAD, the following algorithms have been implemented and simulated.Для иллюстрации возможностей САПР РЛС реализованы и промоделированы следующие алгоритмы.

4.1. Monopulse direction finding algorithm

The model implements the sum-difference direction finding algorithm [13], in which the corrections of the target angular coordinates in the generalized biconical coordinate system are calculated by the formulas:

$$\Delta_u = \hat{u} - u_0 = -\gamma_u \operatorname{Re}\left(\frac{\mathbf{W}_u^H \mathbf{X}}{\mathbf{W}^H \mathbf{X}}\right),$$

$$\Delta_v = \hat{v} - v_0 = -\gamma_v \operatorname{Re}\left(\frac{\mathbf{W}_v^H \mathbf{X}}{\mathbf{W}^H \mathbf{X}}\right),$$

where $\hat{u}$, $\hat{v}$ is the estimation of the target angular coordinates, u_0, v_0 are the angular coordinates of the sum beam maximum, γ_u, γ_v are the slope coefficients of the direction-finding characteristic (determined by the array geometry), $\mathbf{W}$ is the weight vector for the formation of the sum beam, $\mathbf{W}_u$ is the weight vector for the formation of the difference beam in azimuth, $\mathbf{W}_v$ is weight vector for forming a difference beam in elevation, $\mathbf{X}$ is the vector of signals from the antenna array, $(\bullet)^H$ is the Hermitian conjugacy symbol. The denominator of the fractions on the right side of the equalities represents the signal at the output of the sum beam, the numerator is the signal at the output of the difference beam (azimuth or elevation, respectively).

4.2. Direction finding algorithm for stochastic signal sources

For direction finding of sources of stochastic signals, the MUSIC algorithm is implemented, which uses the calculation of the spatial spectrum according to the formula [14]

$$Q_M = \frac{1}{\mathbf{V}^H \hat{\mathbf{P}}_n \mathbf{V}},$$

where $\hat{\mathbf{P}}_n$ is the projection matrix onto the noise subspace of the sample estimate of the spatial covariance matrix $\hat{\mathbf{R}} = \frac{1}{K}\mathbf{X}\mathbf{X}^H$, $\mathbf{V}$ is the hypothesis vector of the amplitude-phase distribution in the antenna opening for a predefined angular direction.

4.3. Adaptive spatial filtering algorithm

The model implements a projection algorithm for calculating the adaptive weight vector according to the formula [14]

$$\mathbf{W}_a = \hat{\mathbf{P}}_n \mathbf{S},$$

where $\mathbf{S}$ is the steering vector.

All of the above algorithms are implemented in the blocks of the radar model in Python using the NumPy and SciPy modules.

5. SIMULATION SCENARIO

The radar model was located in the area of St. Petersburg. Two azimuthally spaced aerodynamic targets were set (**Fig. 3**) with the possibility of assignment stochastic signal sources on them. In terms of their presence, three scenarios were modeled:

1) there are no sources of stochastic signals;
2) one source of stochastic signals;
3) two sources of stochastic signals.

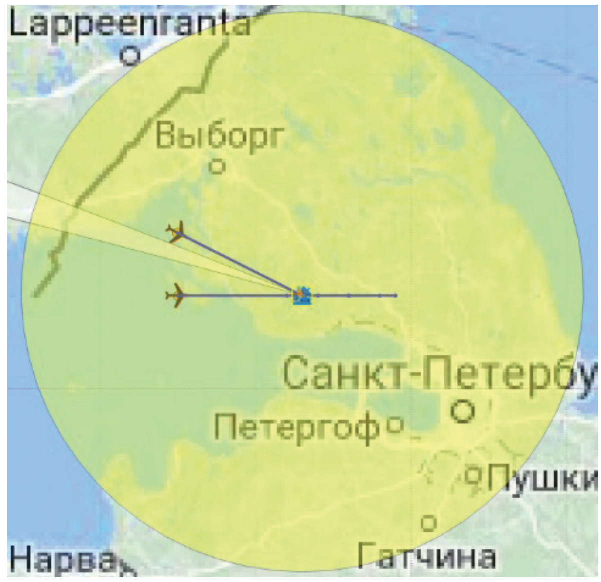

Fig. 3. *The position of the radar and targets.*

5.1. Simulation results

5.1.1. Monopulse direction finding algorithm

The first scenario was used to test the operation of the monopulse direction finding algorithm. The results of the locator for the first target are shown in **Fig. 4**. The figure shows the indicator "azimuth-elevation angle", the yellow circle is the receiving beam at a level of 3 dB, the blue dot is the true position of the target, the red dots are estimates of the angular coordinates of the target. As seen, the implemented monopulse direction finding algorithm correctly refines the angular coordinates of the target.

5.1.2. Direction finding algorithm for stochastic signal sources

Scenario 3 was used to test the operation of the direction finding algorithm for sources of stochastic signals. In this scenario, two sources of stochastic signals were found. Spatial spectrum in the generalized biconical system coordinates (horizontal axis - azimuth, vertical - elevation) is

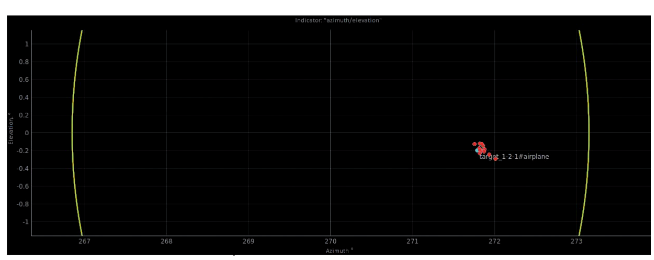

Fig. 4. *Indicator "azimuth-elevation".*

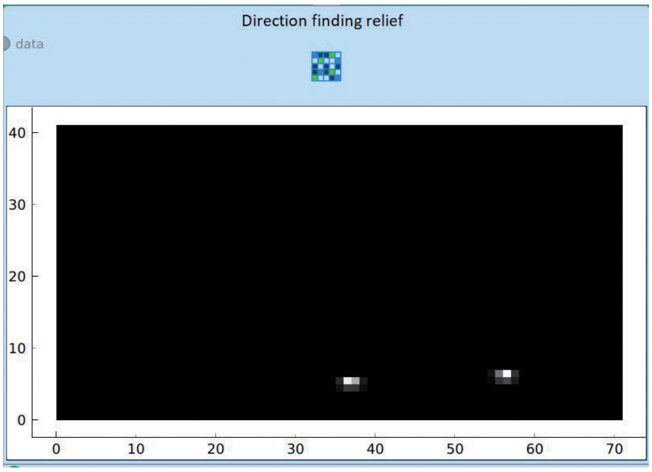

Fig. 5. *Spatial spectrum of MUSIC in scenario 3.*

based on the results of the MUSIC algorithm, is shown in **Fig. 5**. Estimates of the angular coordinates of the sources of stochastic signals in the spherical coordinate system are as follows:

- 1st source – (1.3°; 0.3°), true position – (1.8°; -0.2°);
- 2nd source – (27.5°; 0.3°), true position – (27.2°; -0.2°).

As seen, the estimates coincide with the true position of the sources to within fractions of a degree. When using a grid of angles with a smaller discrete when constructing the spatial spectrum, it is possible to increase the accuracy of the estimate.

5.1.3. Adaptive spatial filtering algorithm

Scenario 2 was used to test the operation of the adaptive spatial filtering algorithm. In the presence of one interfering signal source located on the right target, the central target was detected, marks were issued (yellow markers in **Fig. 6**, blue markers - the true position of the targets). The target with the source of the

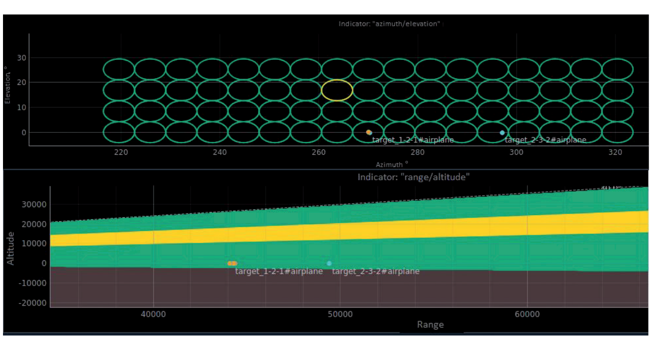

Fig. 6. *Indicators "azimuth-elevation" and "range-altitude" in scenario 2.*

interfering signal was not detected, because the ASF algorithm cannot suppress the interfering signal, the angular direction of which coincides with the direction of the true signal of the target.

6. CONCLUSION

The domestic radar CAD has great opportunities for developing models of radar operation, which make it possible to model in detail the processes of processing various types of signals. For this, a visual functional editor is used, in which the radar model is assembled from a set of blocks. The module of engineering calculation and simulation gives great opportunities to place the created radar model on the ground and set the raid scenario. To demonstrate these capabilities, a model of a sector surveillance radar with electronic beam scanning was created, in which a passive channel is implemented that implements the processing of stochastic signals from external sources. The following algorithms have been implemented and modeled in three scenarios of the interference-target environment: the monopulse direction finding algorithm, the direction finding algorithm for stochastic signal sources, and the adaptive spatial filtering algorithm. The results of the algorithms work correspond to the theoretical forecast.

REFERENCES

1. Kontorov DS, Golubev-Novozhilov YS. *Vvedeniye v radiolokatsionnuyu sistemotekhniku* [Introduction to Radar Systems Engineering]. Moscow, Sovetskoe Radio Publ., 1971, 366 p.
2. Petukhov GB, Yakunin VI. *Metodologicheskiye osnovy vneshnego proyektirovaniya tselenapravlennykh protsessov i tseleustremlennykh system* [Methodological foundations of external design of purposeful processes and purposeful systems]. Moscow, AST Publ., 2006, 504 p.
3. Sozinov PA, Konoval'chik AP. Osnovnyye podkhody k razrabotke otechestvennoy sistemy avtomatizirovannogo proyektirovaniya radiolokatsionnykh stantsiy i tekushchiye rezul'taty [Main approaches

to the development of a domestic system of computer-aided design of radar stations and current results]. *Radioelektronnaya bor'ba*, 2020, 1(1):62-74 (in Russ.).

4. Sozinov PA, Konoval'chik AP, Saushkin VP. Aktual'nyye voprosy sozdaniya otechestvennoy SAPR dlya proyektirovaniya RLS [Topical issues of creating domestic CAD for radar design]. *Vestnik vozdushno-kosmicheskoy oborony,* 2019, 3(23):106-119 (in Russ.).
5. Konoval'chik AP, Konopel'kin MY, Plaksenko OA, Shchiryy AO. Postanovka zadachi razrabotki i predvaritel'naya arkhitektura otechestvennoy SAPR RLS polnogo skvoznogo tsikla [Statement of the task of development and preliminary architecture of the domestic CAD radar of a full end-to-end cycle]. *Novyye informatsionnyye tekhnologii v avtomatizirovannykh sistemakh*, 2017, 20:127-130 (in Russ.).
6. Konoval'chik AP, Plaksenko OA, Shchiryy AO. Kontseptsiya mnogourovnevogo proyektirovaniya RLS v razrabatyvayemoy SAPR RLS polnogo skvoznogo tsikla [The concept of multi-level design of radars in the developed CAD radar of a full end-to-end cycle]. *Fundamental'nyye problemy radioelektronnogo priborostroyeniya*, 2017, 17(4):889-892 (in Russ.).
7. Konoval'chik AP, Konopel'kin MY, Plaksenko OA, Shchiryy AO. Otechestvennaya sistema avtomatizirovannogo proyektirovaniya radiolokatsionnykh sistem, kompleksov i stantsiy s uchetom sredstv vozdushno-kosmicheskogo napadeniya [Domestic system for computer-aided design of radar systems, complexes and stations, taking into account the means of aerospace attack]. *Naukoyemkiye tekhnologii v kosmicheskikh issledovaniyakh Zemli*, 2018, 10(1):40-47 (in Russ.).
8. Konoval'chik AP, Plaksenko OA, Shchiryy AO. Funktsii imitatsii boyevykh deystviy v razrabatyvayemoy otechestvennoy SAPR RLS polnogo skvoznogo tsikla [Functions of simulating combat actions in the developed domestic CAD radar of a full end-to-end cycle]. *Voprosy radioelektroniki*, 2018, 3:30-34 (in Russ.).
9. Konoval'chik AP, Plaksenko OA, Shchiryy AO. Realizatsiya imitatsionnogo modelirovaniya v razrabatyvayemoy otechestvennoy SAPR RLS polnogo skvoznogo tsikla [Implementation of simulation modeling in the developed domestic CAD radar of a full end-to-end cycle]. *Novyye informatsionnyye tekhnologii v avtomatizirovannykh sistemakh*, 2018, 21:290-293 (in Russ.).
10. Konoval'chik AP, Plaksenko OA, Shchiryy AO. Obosnovaniye oblika perspektivnykh radiolokatsionnykh stantsiy posredstvom razrabatyvayemoy otechestvennoy sistemy avtomatizirovannogo proyektirovaniya [Substantiation of the appearance of promising radar stations using the developed domestic computer-aided design system]. *Naukoyemkiye tekhnologii v kosmicheskikh issledovaniyakh Zemli*, 2019, 11(1):4-11 (in Russ.).
11. Van-Roy P, Haridi S. *Concepts, Techniques, and Models of Computer Programming*. Prentice-Hall, 2004, 900 p.
12. Skolnik MI. *Radar Handbook, Third Edition*. McGraw-Hill, 2008.
13. Ratynskiy MV, Porsev VI. *Monoimpul'snaya pelengatsiya v RLS s tsifrovymi FAR* [Monopulse direction finding in radar with digital phased array]. Moscow, Radiotekhnika Publ., 2019, 160 p.
14. Van Trees HL. *Detection, estimation and modulation theory. Part IV. Optimum array processing*. Wiley, 2002.