Modern radio engineering and telecommunication systems

Современные радиотехнические и телекоммуникационные системы

UDC 004.94
https://doi.org/10.32362/2500-316X-2022-10-5-49-59

RESEARCH ARTICLE

Implementation of stochastic signal processing algorithms in radar CAD

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Abstract
Objectives. In 2020, development work on the creation of a Russian computer-assisted design system for radars (radar CAD) was completed. Radar CAD provides extensive opportunities for creating simulation models for developing the hardware-software complex of radar algorithms, which take into account the specific conditions of aerospace environment observation. The purpose of the present work is to review and demonstrate the capabilities of radar CAD in terms of implementing and testing algorithms for processing stochastic signals.
Methods. The work is based on the mathematical apparatus of linear algebra. Analysis of algorithms characteristics was carried out using the simulation method.
Results. A simulation model of a sector surveillance radar with a digital antenna array was created in the radar CAD visual functional editor. The passive channel included the following algorithms: algorithm for detecting stochastic signals; algorithm for estimating the number of stochastic signals; direction finding algorithm for stochastic signal sources; adaptive spatial filtering algorithm. In the process of simulation, the algorithms for detecting and estimating the number of stochastic signals produced a correct detection sign and an estimate of the number of signals. The direction-finding algorithm estimated the angular position of the sources with an accuracy of fractions of degrees. The adaptive spatial filtering algorithm suppressed interfering signals to a level below the antenna's intrinsic noise power.
Conclusions. The processing of various types of signals can be simulated in detail on the basis of the Russian radar CAD system for the development of functional radar models. According to the results of the simulation, coordinates of observing objects were obtained and an assessment of the effectiveness of the algorithms was given. The obtained results are fully consistent with the theoretical prediction. The capabilities of radar CAD systems demonstrated in this work can be used by specialists in the field of radar and signal processing.

Keywords: simulation modeling, radar information processing algorithm, computer-aided design system, radar station, adaptive spatial filtering

• **Submitted:** 05.05.2022 • **Revised:** 15.07.2022 • **Accepted:** 02.09.2022

For citation: Konopel'kin M.Yu., Petrov S.V., Smirnyagina D.A. Implementation of stochastic signal processing algorithms in radar CAD. *Russ. Technol. J.* 2022;10(5):49–59. https://doi.org/10.32362/2500-316X-2022-10-5-49-59

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Реализация алгоритмов обработки стохастических сигналов в САПР РЛС

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Резюме
Цели. В 2020 г. завершилась опытно-конструкторская работа по созданию российской системы автоматизированного проектирования (САПР) радиолокационных станций (РЛС). Отличительной особенностью САПР РЛС являются богатые возможности для создания имитационных моделей и имитационного моделирования, что позволяет отрабатывать аппаратную часть и комплекс боевых алгоритмов РЛС с учетом конкретных условий боевого применения, средств воздушно-космического нападения и фоно-целевой обстановки. Цель настоящей статьи – обзор и демонстрация возможностей САПР РЛС в части реализации и отработки алгоритмов обработки стохастических сигналов.
Методы. В работе использовался математический аппарат линейной алгебры. Анализ характеристик алгоритмов проведен методом имитационного моделирования.
Результаты. В визуальном функциональном редакторе САПР РЛС создана имитационная модель РЛС секторного обзора с цифровой антенной решеткой. В состав пассивного канала входили следующие алгоритмы: алгоритм обнаружения стохастических сигналов; алгоритм оценивания числа стохастических сигналов; алгоритм пеленгации источников стохастических сигналов; алгоритм адаптивной пространственной фильтрации. В процессе имитационного моделирования алгоритмы обнаружения и оценивания числа выдавали корректный признак обнаружения и оценку числа сигналов. Алгоритм пеленгации оценивал угловое положение источников с точностью до долей градусов. Алгоритм адаптивной пространственной фильтрации подавлял сигналы мешающих сигналов до уровня ниже мощности собственных шумов антенны.
Выводы. Обширные возможности по разработке моделей функционирования РЛС, имеющиеся в российской САПР РЛС, позволяют детально моделировать процессы обработки различных видов сигналов. По результатам моделирования получены координаты целей и приведена оценка эффективности работы алгоритмов. Полученные результаты полностью соответствуют теоретическому прогнозу. Продемонстрированные в настоящей работе возможности САПР РЛС могут быть использованы специалистами в области радиолокации и обработки сигналов.

Ключевые слова: имитационное моделирование, алгоритм обработки радиолокационной информации, система автоматизированного проектирования, радиолокационная станция, адаптивная пространственная фильтрация

• **Поступила:** 05.05.2022 • **Доработана:** 15.07.2022 • **Принята к опубликованию:** 02.09.2022

Для цитирования: Конопелькин М.Ю., Петров С.В., Смирнягина Д.А. Реализация алгоритмов обработки стохастических сигналов в САПР РЛС. *Russ. Technol. J.* 2022;10(5):49–59. https://doi.org/10.32362/2500-316X-2022-10-5-49-59

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

In 2020, development work was completed on the creation of a computer-assisted design (CAD) system for radar stations, radar complexes and radar systems, as well as their various components [1–10]. Due to the outstanding capabilities of radar CAD in creating simulation models and simulation modeling, it is now possible to work out a hardware and algorithm set for the radar that takes specific conditions of aerospace environment observation. One of the most important applications of the developed CAD is the development of algorithms for processing radar information based on the results of end-to-end integrated simulation based on the requirements and operating conditions.

The study aimes to review and demonstrate the capabilities of radar CAD in terms of implementing and developing algorithms for processing stochastic signals.

1. RADAR CAD TOOLKIT

1.1. Visual functional editor

Radar CAD uses an approach known as dataflow programming to create simulation models. Employing the visual constructor, a user 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 passed through; the output data of each block are calculated based on the input data and block parameters.

The advantages of this approach are the natural visual representation (in the form of a calculation graph) and support for parallelism. The visual functional editor developed as part of the radar CAD system provides the ability to create and calculate a data-flow graph. The graphical user interface resembles the classic *Simulink* interface for visual design of streaming data processing, consisting of interconnected parameterizable blocks (Fig. 1).

1.2. Module of engineering calculation and simulation

As well as the possibility of automating the radar development process, another of the key features of the developed CAD is its comprehensive modeling of radar behavior under operating conditions. In particular, an engineer has the possibility to set a scenario as part of the design process. When sending the scenario for calculation, a complete (close to reality) simulation of the behavior of the radar under operating conditions is carried out. A simulated raid on the radar includes the simulation of the movement of various air objects. At the same time, the operation of the radar antenna is modeled on the basis of the constructed radar model to scan the space. The reflection of an electromagnetic wave from an air object is simulated during the interaction of electromagnetic waves coming from the locator antenna and the air object to form the basis of calculated parameters of the signal received by the appropriate channel of the locator, where its processing can be further simulated. Various types of noise are superimposed on the incoming signal, due, for example, to reflection from the Earth's surface. When modeling the propagation of a beam through the atmosphere, various kinds of precipitation are also taken into account.

The modeling process is organized by the simulation modeling manager (SMM). The creation and editing of simulation scenarios is implemented in the module of engineering calculation and simulation (Fig. 2), which is part of the radar CAD system.

2. DESCRIPTION OF THE RADAR SIMULATION MODEL

2.1. Parameters of the radar simulation model

To demonstrate the capabilities of radar CAD in terms of implementing and testing algorithms for processing stochastic signals, a radar simulation model of an airspace surveillance was created. Figure 3 shows its block diagram, which includes the transmitting and receiving parts: the radio transmitter generates pulses with specified modulation parameters, while the radio receivers, together with the primary information processing system and the passive channel, provide amplification, conversion and optimal processing of the signals received by the antenna against a background of internal noise and external interference.

The radar type is active, single position, sector surveillance with electronic beam scanning. The selected signal parameters are typical for air traffic control radar [11]:

- signal type: chirp;
- carrier frequency: 3 GHz;
- signal bandwidth: 1 MHz;
- pulse duration: 67 μs;
- pulse repetition period: 0.67 ms;
- pulse power: 2.3 kW.

Antenna parameters are as follows:

- type of antenna: digital antenna array (DAA);
- size, in elements: 12 × 12;
- step of elements: 0.5 wavelength;
- gain factor: 32 dB;
- scanning sector in azimuth: (−45°)–(+45°);
- scanning sector in elevation: 0°–30°;
- antenna tilt to the horizon: 15°.

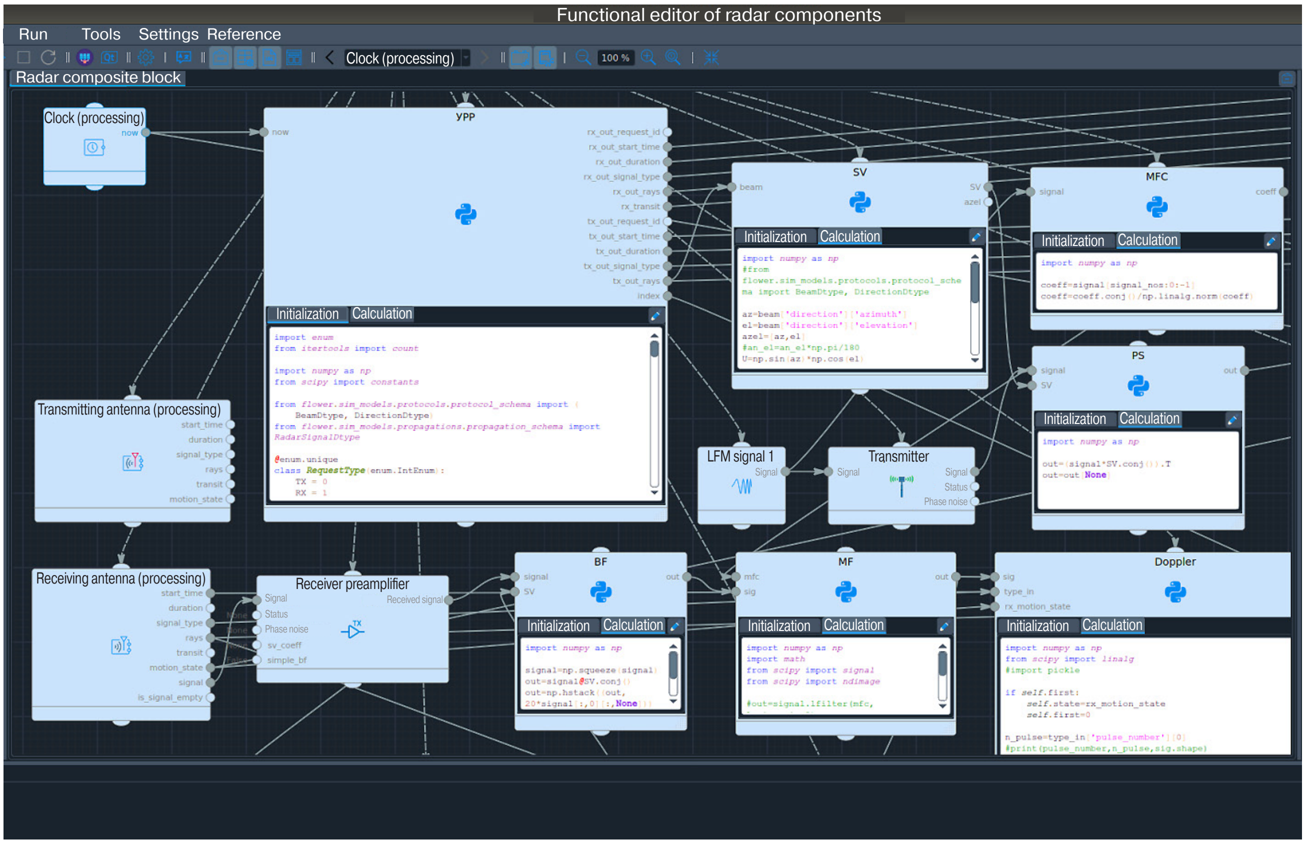

Fig. 1. Visual functional editor and radar model blocks

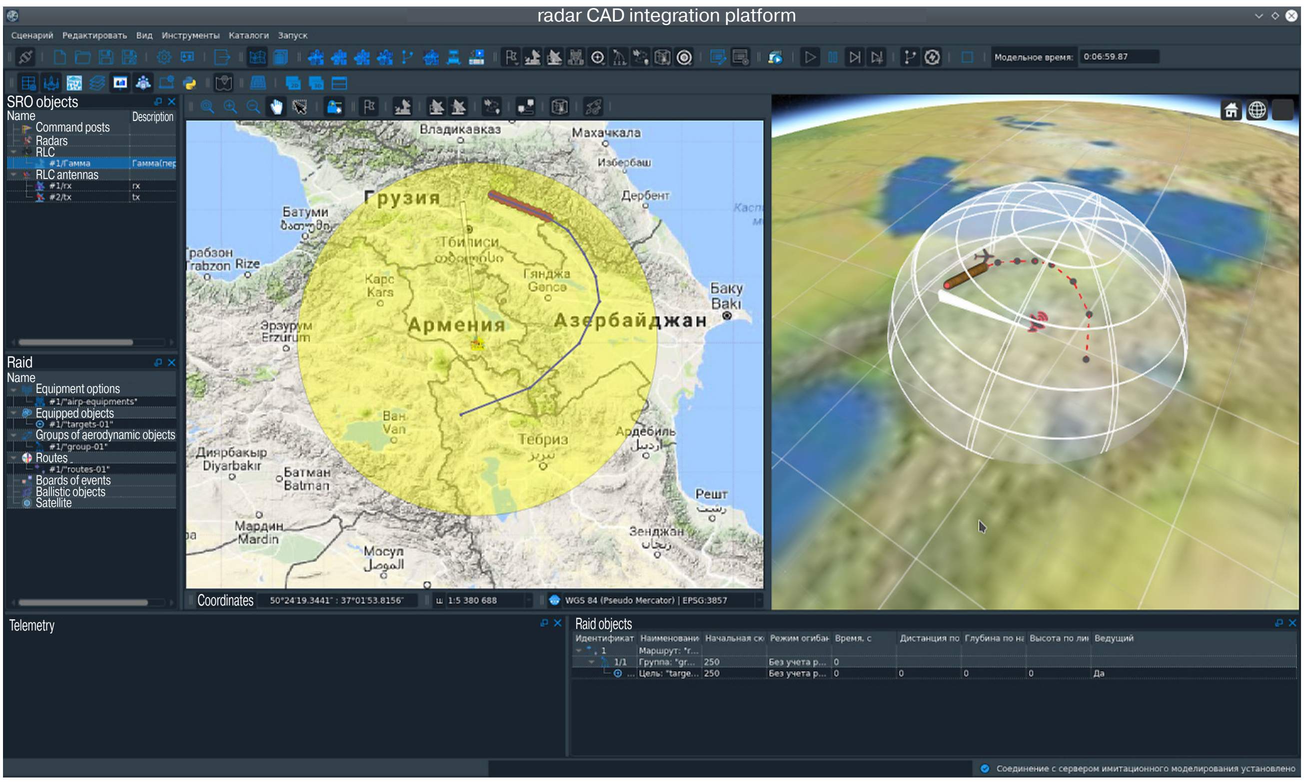

Fig. 2. Interface of the module of engineering calculation and simulation

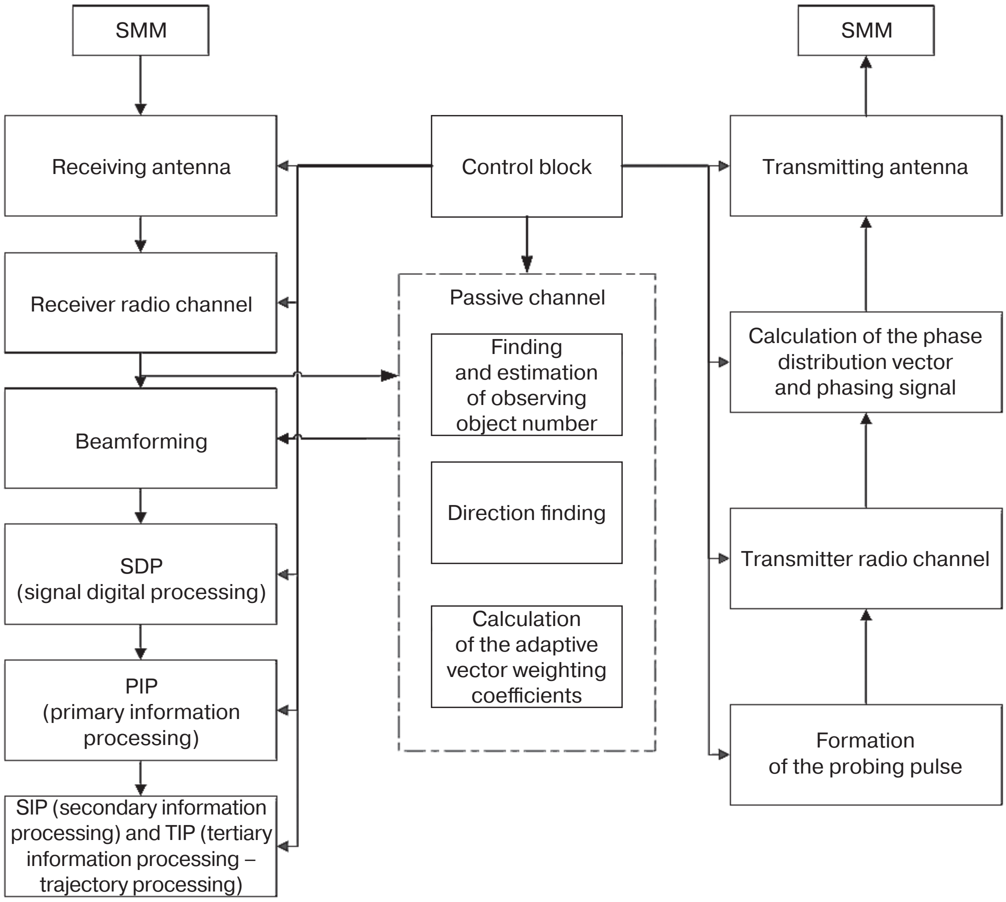

Fig. 3. Block-diagram of radar CAD

The radar model implements a passive channel for processing stochastic signals from external sources. In this case, training data comprising time samples with a DAA of length $K = 256$ are used.

2.2. Radar simulation algorithms

Algorithm for detecting stochastic signals

The model implements an asymptotically optimal algorithm for detecting stochastic signals using the decision statistics obtained from the generalized likelihood ratio test criterion [12]:

$$Q_{\mathrm{D}} = \frac{N\hat{\lambda}_1}{Tr\hat{\mathbf{R}}}, \quad (1)$$

where N is the number of DAA elements; $\hat{\mathbf{R}} = \frac{1}{K}\mathbf{X}\mathbf{X}^{\mathrm{H}}$ is the sample estimate of the correlation matrix; $\mathbf{X}$ is the training data package; Tr is the trace of the matrix; $\hat{\lambda}_1$ is the maximum eigenvalue of the matrix $\hat{\mathbf{R}}$.

Algorithm for estimating the number of stochastic signals

The model implements an asymptotically optimal algorithm for estimating the number of stochastic signals

$$\hat{M} = \arg\min_n \left(Q_n < d_n(\alpha)\right) - 1, \ n = 1, \ldots, N, \quad (2)$$

where $d_n(\alpha)$ is the threshold calculated from the given false alarm level α; Q_n is the decision statistic obtained from the generalized likelihood ratio test [13]:

$$Q_n = \frac{(N - n + 1)\hat{\lambda}_n}{\sum_{i=n}^{N} \hat{\lambda}_i}, \quad (3)$$

where $\hat{\lambda}_i$ is the ith largest eigenvalue of the matrix $\hat{\mathbf{R}}$.

Algorithm for direction finding of sources of stochastic signals

For direction finding of sources of stochastic signals, the Capon algorithm is implemented, which uses the calculation of the spatial spectrum [14, 15]:

$$Q_{\mathrm{C}} = \frac{1}{\mathbf{V}^{\mathrm{H}}\hat{\mathbf{R}}^{-1}\mathbf{V}}, \quad (4)$$

where $\mathbf{V}$ is a hypothesis vector; $(\cdot)^{\mathrm{H}}$ is the Hermitian conjugacy symbol.

Adaptive spatial filtering (ASF) algorithm

The model implements the calculation of the adaptive weight vector according to the formula [14, 15]:

$$\mathbf{W} = \hat{\mathbf{R}}^{-1}\mathbf{S}, \quad (5)$$

where **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.

3. SIMULATION MODELLING RESULTS

3.1. Simulation modeling scenario

To carry out the simulation, a model of a sector surveillance radar with electronic beam scanning was created. This model includes a passive channel that implements the processing of stochastic signals from external sources. The radar model was located in the area of St. Petersburg. Two azimuthally separated aerodynamic objects of observation were set (Fig. 4) with the option of installing stochastic signal sources on them. In terms of their presence, three scenarios were modeled:

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

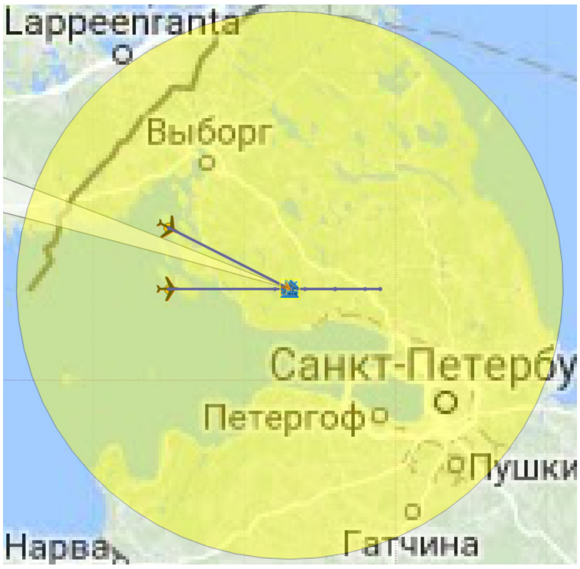

Fig. 4. Position of the radar and objects of observation

3.2. Results of the algorithms operation for detecting and estimating the number of sources

In the first scenario, the algorithms for detecting and estimating the number of sources showed the expected results—the sign of detection and estimate of the number are equal to zero. Figure 5 shows the result of the operation of these algorithms for several cycles of radar operation—the cycles of transmission and reception.

In the second scenario, the algorithms for detecting and estimating the number showed the expected results—the sign of detection and the estimate of the number of sources are equal to one (Fig. 6).

In the third scenario, the algorithms for detecting and estimating the number also showed the expected results—the detection sign is equal to one, while the estimated number is two (Fig. 7).

3.3. Results of the direction-finding algorithm

In the first scenario, there are no results, because the direction-finding algorithm is started only if the sign of detection is equal to one.

In the second scenario, one source of stochastic signals is located. Figure 8 shows the spatial spectrum in the generalized biconical coordinate system (GBCS) (the horizontal axis is the azimuth, the vertical axis is the elevation), built according to the results of the algorithm.

In the third scenario, two sources of stochastic signals are located. Figure 9 shows the spatial spectrum in the GBCS (the horizontal axis is the azimuth; the vertical axis is the elevation) constructed based on the results of the algorithm

The 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 can be seen, the estimates coincide with the true position of the sources to within fractions of a degree. A further increase in the accuracy of the estimate is possible when using a grid of angles with a smaller discrete to construct the spatial spectrum.

3.4. Results of the ASF algorithm

In the absence of interfering signals, both objects of observation were detected, with marks being issued for them (yellow markers in Fig. 10). In this scenario, in the absence of interfering signals (the detection sign is equal to zero), the ASF algorithm was not activated, and a non-adaptive beam was formed for reception.

In the presence of one source of interfering signal placed on the right object of observation, the central object of observation was detected; marks were issues for it (yellow markers in Fig. 11, blue markers—the true position of the object of observation). No object of observation whose source comprised an

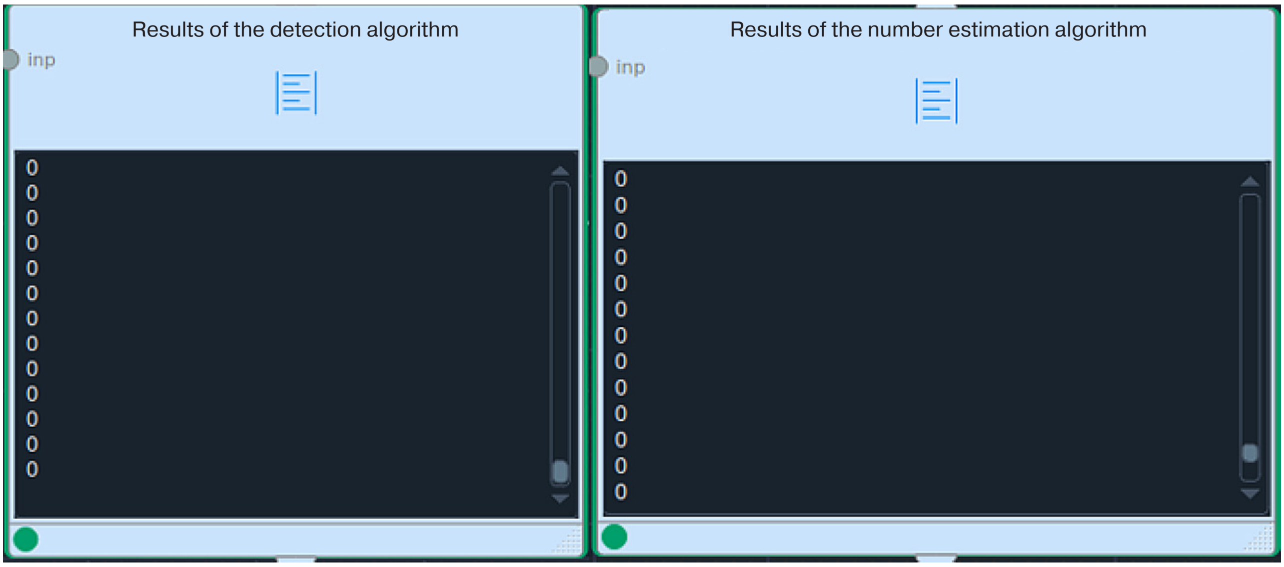

Fig. 5. Output of algorithms for detecting and estimating the number in a scenario 1

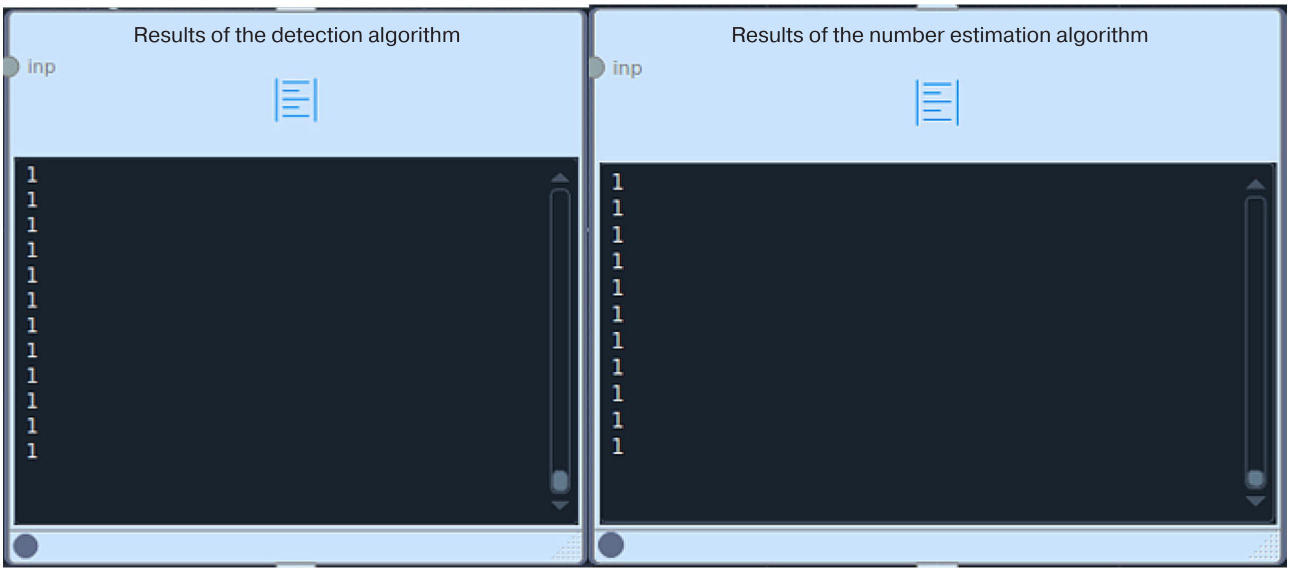

Fig. 6. Output of the algorithm for detecting and estimating the number in scenario 2

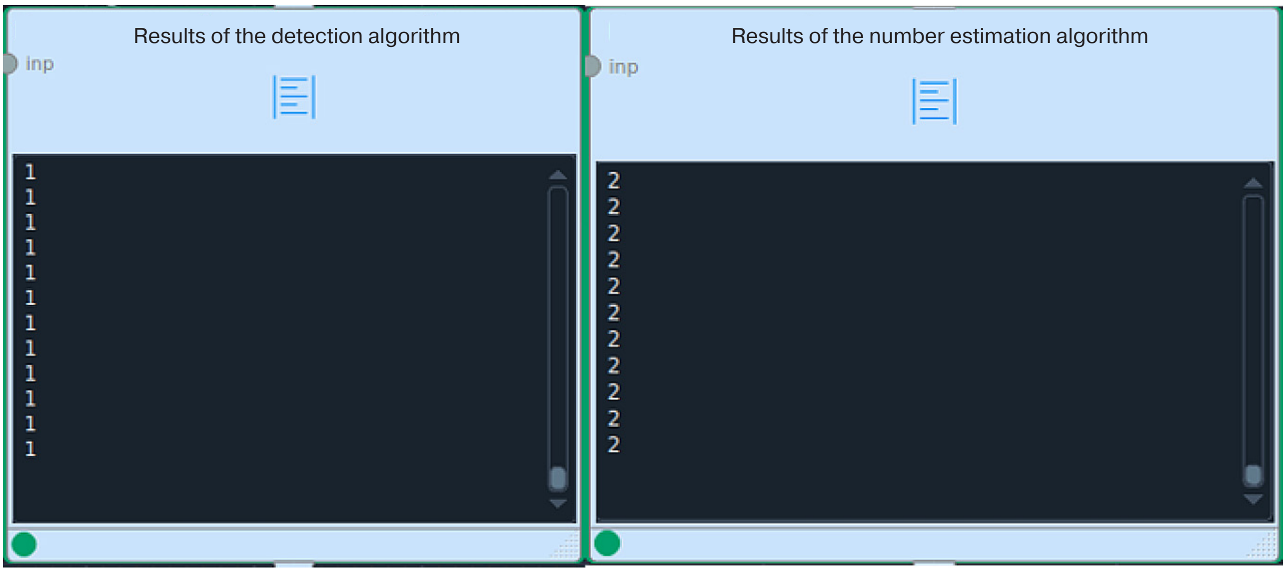

Fig. 7. Output of the algorithm for detecting and estimating the number in scenario 3

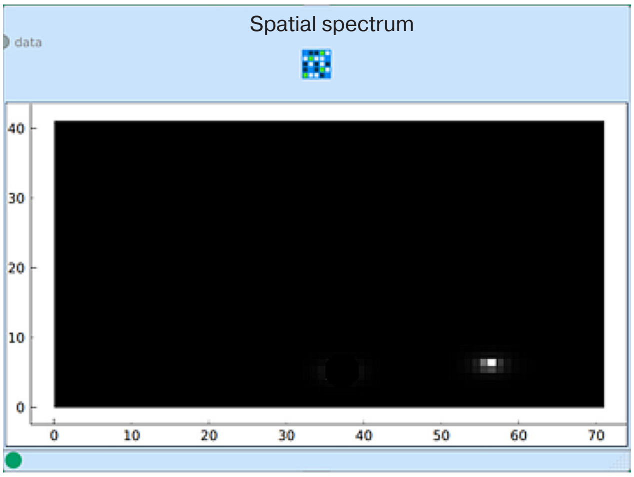

Fig. 8. Algorithm output for direction finding in Scenario 2

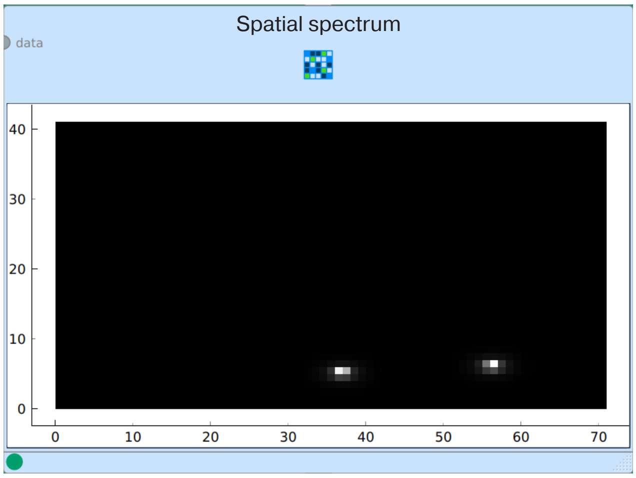

Fig. 9. Algorithm output for direction finding in Scenario 3

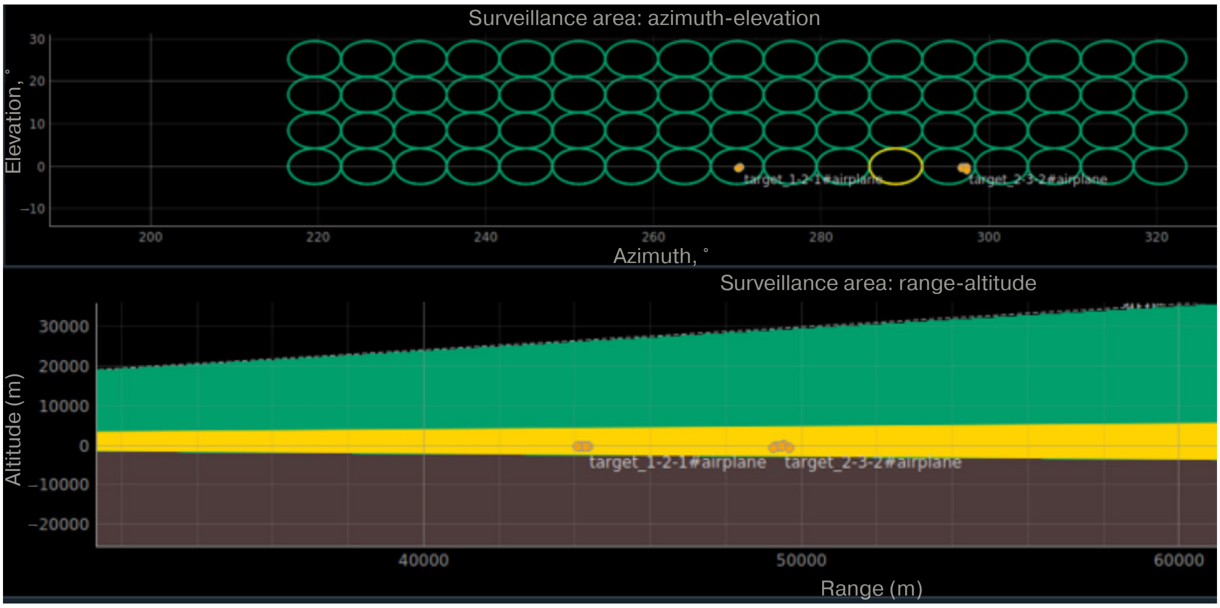

Fig. 10. Indicators "azimuth-elevation" and "range-altitude" in scenario 1

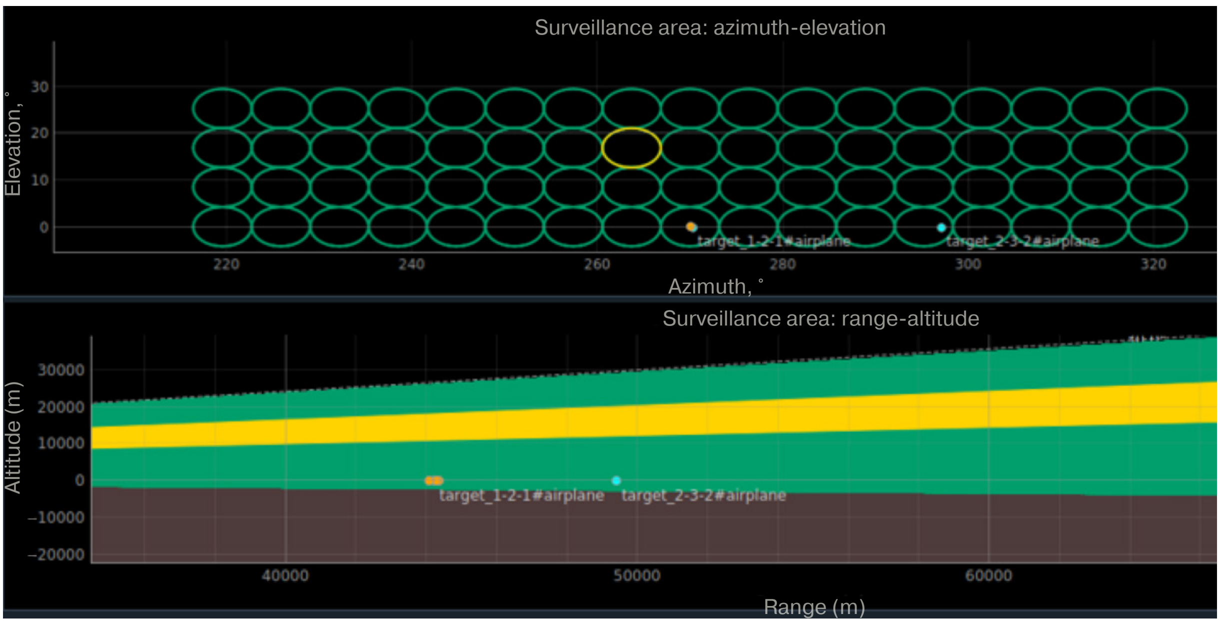

Fig. 11. Indicators "azimuth-elevation" and "range-altitude" in scenario 2

interfering signal was detected because the ASF algorithm cannot suppress an interfering signal if its angular direction coincides with the direction of the useful signal.

In the presence of two interfering signals, the objects of observation were not detected.

Let us estimate the efficiency of the ASF algorithm based on the results of the simulation. To do this, it is necessary to find the values of the following quantities before and after adaptation [16]:

- power of the useful signal at the output of the array;
- interference to noise ratio at the output in terms of power (INR);
- signal to interference + noise power ratio (SINR).

To calculate these values, the following parameters were calculated:

- useful signal output power

$$P_S = \sigma_S^2 \left|\mathbf{W}^H \mathbf{V}_S\right|^2, \qquad (6)$$

where σ_S^2 is the signal power in the array element; $\mathbf{W}$ is the weight vector; $\mathbf{V}_S$ is the vector of the amplitude-phase distribution of the field of the useful signal in the array opening;

- output power of interferences and noises

$$P_{JN} = \mathbf{W}^H \hat{\mathbf{R}} \mathbf{W} = \frac{1}{K}\left\|\mathbf{W}^H \mathbf{X}\right\|^2, \qquad (7)$$

where $\|\cdot\|$ is the Euclidean norm of the vector;

- intrinsic noise power at the array output

$$P_N = \sigma_N^2 \left\|\mathbf{W}\right\|^2, \qquad (8)$$

where σ_N^2 is the intrinsic noise power in the array element.

To obtain a more accurate estimation, the data packet $\mathbf{X}$ used when calculating the output power of interference and noise was different from that used to calculate the adaptive weight vector. The estimates are given in Table. As follows from the presented results, the interference was suppressed almost completely to a level below the intrinsic noise of the antenna array.

Table. Results of evaluation of the effectiveness of ASF

Evaluated values	Before ASF	After ASF
P_S, dB	−94.4	−94.4
P_{JN}, dB	−85.0	−118.0
P_N, dB	−118.1	−118.1
INR, dB	33.1	−16.4
SINR, dB	−9.4	23.6

In order to illustrate the operation of the algorithm, Fig. 12 shows a section of the phased array antenna (PAA) pattern in scenario 2. The observed deep dip formed in the pattern in the direction of the interference confirms the correct operation of the algorithm.

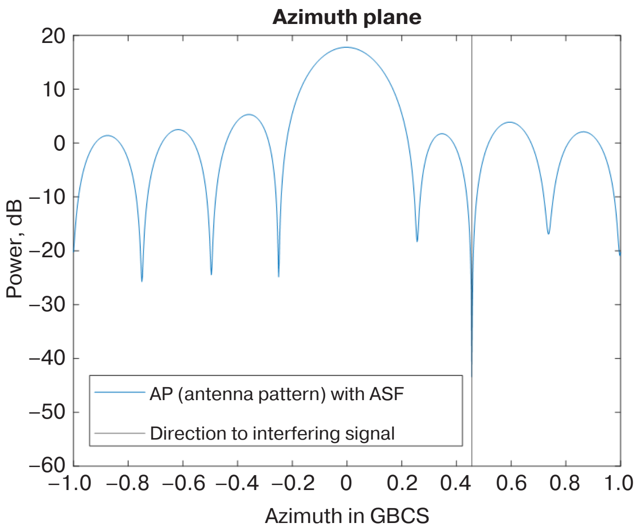

Fig. 12. Section of the PAA pattern

CONCLUSIONS

The Russian radar CAD system presents great opportunities for developing radar operation models, allowing the processing of various types of signals to be simulated in detail. For this purpose, a visual functional editor is used in which the radar model is built from a set of blocks. The module of engineering calculation and simulation allows the created radar model to be placed on the ground along with the preset raid scenario. To demonstrate these capabilities, a model of a sector surveillance radar with electronic beam scanning was created in which the implemented passive channel uses the processing of stochastic signals from external sources. Simulation modeling was carried out according to three scenarios of the aerospace environment. The results of the algorithms are fully consistent with the theoretical prediction.

Authors' contributions

M.Yu. Konopel'kin—conducting research, configuring radar model templates, setting a tactical task, setting up a noise/signal environment, and editing the text of the article.

S.V. Petrov—adaptation of the algorithms for using in a CAR radar and their implementation, script development, conducting simulation experiments, and writing the text of the article.

D.A. Smirnyagina—implementing the algorithms, conducting simulation experiments, analyzing the results obtained, and writing the text of the article.

REFERENCES

1. Sozinov P.A., Konoval'chik A.P., Saushkin V.P. Relevant questions of indigenous CAD development for radar engineering. *Vestnik vozdushno-kosmicheskoi oborony = Aerospace Defense Herald*. 2019;3(23):106–119 (in Russ.).
2. Sozinov P.A., Konoval'chik A.P. Basic approaches to the development of a domestic system of automated design of radar stations and current results. *Radiotekhnika = Radioengineering.* 2020;84(7–13):62–74 (in Russ.). https://doi.org/10.18127/j00338486-202007(13)-08
3. Konoval'chik A.P., Konopel'kin M.Yu., Shchiryi A.O., Arutyunyan A.A. Stages of designing advanced radar stations in specialized domestic CAD system. *Vestnik vozdushno-kosmicheskoi oborony = Aerospace Defense Herald.* 2020;4(28):111–119 (in Russ.).
4. Konoval'chik A.P. Computer-aided design of radar stations: principles for constructing the design process. *Vestnik vozdushno-kosmicheskoi oborony = Aerospace Defense Herald.* 2021;2(30):52–64 (in Russ.).
5. Konoval'chik A.P., Konopel'kin M.Yu., Plaksenko O.A., Shchiryi A.O. Statement of the task of development and preliminary architecture of the domestic CAD radar of a full end-to-end cycle. *Novye informatsionnye tekhnologii v avtomatizirovannykh sistemakh = New Information Technologies in Automated Systems.* 2017;20:127–130 (in Russ.).
6. Konoval'chik A.P., Plaksenko O.A., Shchiryy A.O. 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 = Fundamental Problems of Radio-Electronic Instrumentation.* 2017;17(4):889–892 (in Russ.).
7. Konoval'chik A.P., Konopel'kin M.Y., Plaksenko O.A., Shchiryy A.O. 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 = H&ES Research.* 2018;10(1):40–47 (in Russ.).
8. Konoval'chik A.P., Plaksenko O.A., Shchiryy A.O. Functions of simulating combat actions in the developed domestic CAD radar of a full end-to-end cycle. *Voprosy radioelektroniki= Issues of Radio Electronics*. 2018;3:30–34 (in Russ.).
9. Konoval'chik A.P., Plaksenko O.A., Shchiryy A.O. Implementation of simulation modeling in the developed domestic CAD radar of a full end-to-end cycle. *Novyye informatsionnyye tekhnologii v avtomatizirovannykh sistemakh = New Information Technologies in Automated Systems*. 2018;21:290–293 (in Russ.).
10. Konoval'chik A.P., Plaksenko O.A., Shchiryy A.O. Substantiation of the appearance of promising radar stations using the developed domestic computer-aided design system. *Naukoyemkiye tekhnologii v kosmicheskikh issledovaniyakh Zemli = H&ES Research*. 2019;11(1):4–11 (in Russ.).
11. Skolnik M.I. *Radar Handbook*. Third Edition. McGraw-Hill; 2008. 1328 p.

СПИСОК ЛИТЕРАТУРЫ

1. Созинов П.А., Коновальчик А.П., Саушкин В.П. Актуальные вопросы создания отечественной САПР для проектирования РЛС. *Вестник воздушно-космической обороны*. 2019;3(23):106–119.
2. Созинов П.А., Коновальчик А.П. Основные подходы к разработке отечественной системы автоматизированного проектирования радиолокационных станций и текущие результаты. *Радиотехника*. 2020;84(7–13): 62–74. https://doi.org/10.18127/j00338486-202007(13)-08
3. Коновальчик А.П., Конопелькин М.Ю., Щирый А.О., Арутюнян А.А. Этапы проектирования перспективных радиолокационных станций в специализированной САПР. *Вестник воздушно-космической обороны.* 2020;4(28):111–119.
4. Коновальчик А.П. Система автоматизированного проектирования радиолокационных станций: принципы построения процесса проектирования. *Вестник воздушно-космической обороны.* 2021;2(30): 52–64.
5. Коновальчик А.П., Конопелькин М.Ю., Плаксенко О.А., Щирый А.О. Постановка задачи разработки и предварительная архитектура отечественной САПР РЛС полного сквозного цикла. *Новые информационные технологии в автоматизированных системах.* 2017;20:127–130.
6. Коновальчик А.П., Плаксенко О.А., Щирый А.О. Концепция многоуровневого проектирования РЛС в разрабатываемой САПР РЛС полного сквозного цикла. *Фундаментальные проблемы радиоэлектронного приборостроения.* 2017;17(4):889–892.
7. Коновальчик А.П., Конопелькин М.Ю., Плаксенко О.А., Щирый А.О. Отечественная система автоматизированного проектирования радиолокационных систем, комплексов и станций с учетом средств воздушно-космического нападения. *Наукоемкие технологии в космических исследованиях Земли.* 2018;10(1):40–47.
8. Коновальчик А.П., Плаксенко О.А., Щирый А.О. Функции имитации боевых действий в разрабатываемой отечественной САПР РЛС полного сквозного цикла. *Вопросы радиоэлектроники.* 2018;3:30–34.
9. Коновальчик А.П., Плаксенко О.А., Щирый А.О. Реализация имитационного моделирования в разрабатываемой отечественной САПР РЛС полного сквозного цикла. *Новые информационные технологии в автоматизированных системах.* 2018;21:290–293.
10. Коновальчик А.П., Плаксенко О.А., Щирый А.О. Обоснование облика перспективных радиолокационных станций посредством разрабатываемой отечественной системы автоматизированного проектирования. *Наукоемкие технологии в космических исследованиях Земли.* 2019;11(1):4–11.
11. Skolnik M.I. *Radar Handbook*. Third Edition. McGraw-Hill; 2008. 1328 p.
12. Петров С.В. Синтез и анализ алгоритмов обнаружения стохастических сигналов в системах с многоэлементной антенной решеткой. *Антенны.* 2015;7: 29–36.

12. Petrov S.V. Synthesis and analysis of stochastic signal detection algorithms in the multi-element antenna array systems. *Antenny = Antennas*. 2015;7:29–36 (in Russ.).
13. Petrov S.V. Synthesis and analysis of the algorithm for estimating the number of stochastic signals in systems with a multi-element antenna array. *Antenny = Antennas.* 2015;9:15–22 (in Russ.).
14. Ratynskii M.V. *Adaptatsiya i sverkhrazreshenie v antennykh reshetkakh* (*Adaptation and Superresolution in Antenna Arrays*). Moscow: Radio i svyaz'; 2003. 200 p. (in Russ.).
15. Van Trees H.L. *Detection, estimation and modulation theory. Part IV. Optimum array processing.* Wiley; 2002. 1443 p.
16. Ratynskiy M.V. On the evaluation of adaptive spatial filtering efficiency. *Radiotekhnika = Radioengineering*. 2013;8:38–44 (in Russ.).

13. Петров С.В. Синтез и анализ алгоритма оценивания числа стохастических сигналов в системах с многоэлементной антенной решеткой. *Антенны.* 2015;9:15–22.
14. Ратынский М.В. *Адаптация и сверхразрешение в антенных решетках.* М.: Радио и связь; 2003. 200 с.
15. Van Trees H.L. *Detection, estimation and modulation theory. Part IV. Optimum array processing.* Wiley; 2002. 1443 p.
16. Ратынский М.В. Оценка эффективности адаптивной пространственной фильтрации. *Радиотехника.* 2013;8:38–44.

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Translated from Russian into English by Evgenii I. Shklovskii
Edited for English language and spelling by Thomas A. Beavitt