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IMPROVING A METHOD FOR DETECTING STEALTH AERIAL VEHICLES BY USING A NETWORK OF TWO SMALL-SIZED RADARS WITH DECENTRALIZED INFORMATION PROCESSING

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The object of this study is the process of detecting stealth aerial vehicles by a network of two small-sized radars with decentralized signal processing. The main hypothesis of the study assumed that combining two small-sized radars into a network could improve the quality of detection of stealth aerial vehicles with decentralized signal processing.

The improved method for detecting a stealth aerial vehicle by a network of two small-sized radars with decentralized processing, unlike the known ones, provides for the following:

– each radar emits its own probing signal;

– each radar receives only its own signal;

– coordinated filtering in the reception system of each radar of its signal;

– quadratic detection of its signal in each radar;

– finding the sum of detected signals in each radar at the output of its matched filter;

– preliminary detection of the signal is carried out by each radar separately;

– in each range element, the signal is compared with the threshold level;

– when the threshold level in the range element is exceeded, such range element is assigned a value of one, otherwise – zero;

– the sequence of zeros and ones obtained in this way in each radar of the network is transmitted to the central processing point;

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element. Such a decision is made based on the results of the combined processing of binary sequences coming from the radars according to the "k out of m" criterion.

It was established that when detecting a stealth aerial vehicle by a network of two small-sized radars, decentralized information processing provides a higher value of the conditional probability of correct detection, by (19–26) % on average

Keywords: small-sized radar, aerial object detection, decentralized processing, conditional probability of correct detection

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1. Introduction

Small-sized radars are an integral part of modern mobile air defense systems, for example [1, 2]. The use of mobile systems is due to the need to maneuver after completing the task. The maneuver is due to the need to get out from under a possible attack of the enemy's means of destruction, which has been proven by the experience of, for example, the modern conflict in the Middle East and the Russian-Ukrainian war [3, 4].

The small size and mobility of modern radars imposes certain limitations on the quality indicators of detection of aerial objects, especially stealth aerial vehicles [5]. Such limitations are primarily associated with a decrease in the signal/noise ratio and, accordingly, a decrease in the conditional probability of correct detection of a stealth aerial vehicle. Stealth aerial vehicles include cruise missiles, unmanned aerial vehicles, etc., for example [6, 7].

An effective way to improve the quality of detection of stealth aerial vehicles is the use of small-sized radars that are connected to each other in a network, for example, [8–10]. The construction of such multi-radar networks involves the processing by each radar of both its own signal and the signal from another network radar. This, in turn, requires ensuring the synchronous operation of network elements in space and time, which cannot always be ensured. This problem is especially aggravated by incoherent processing of signals from a stealth aerial vehicle.

In this case, it is expedient to switch to decentralized signal processing by each radar of the multi-radar network, followed by combining information (joint signal processing) to detect a stealth aerial vehicle.

Therefore, devising a method for detecting stealth aerial vehicles using a network of two small-sized radars with decentralized signal processing is an urgent task.

2. Literature review and problem statement

In [8], it is proposed to use probing signals with a complex structure in radars. This will certainly increase the conditional probability of correct detection. The disadvantage [8] is the impossibility of changing the sounding signal structure in small-sized radars.

In [9], a narrowing of the width of the antenna directional pattern is suggested. But, as a rule, the directional pattern of small-sized radars is relatively wide. This makes it impossible to use the method from [9] for small-sized radars.

In [10], the general theoretical foundations of the construction of multiradar systems are outlined. Work [10] is basic for understanding the principles of building multiradar systems. The disadvantage of [10] is its theoretical orientation, which makes it impossible to directly use [10] in small-sized radars.

In [11], the method for organizing the operation of so-called radar networks, which are built according to the principle of MIMO (Multiple Input – Multiple Output), is considered. Theoretical calculations of spatial and temporal indicators of the operation of such systems are presented. The disadvantage of [11] is the failure to take into account the limitations of using MIMO systems for small-sized radars.

In [12], the method of building a MIMO network of radars with mechanical rotation of the antenna system is considered. The disadvantage of [12] is the complexity of building such a system based on radars with a mechanical survey of the airspace.

In [13], it is proposed to improve the detection indicators of a stealth aerial vehicle at the expense of additional energy of extraneous cellular signals. The disadvantage of [13] is the impossibility of ensuring the synchronous operation of communication stations and small-sized radars.

In [14], the use of the principle of multilateration and systems operating according to this principle is proposed. At the same time, the so-called MLAT methods are used to detect stealth aerial vehicles. The disadvantage of [14] is the limitation of MLAT methods in terms of range and, accordingly, the impossibility of their application in small-sized radars.

In [15], it is proposed to improve the detection indicators of a stealth aerial vehicle at the expense of additional energy of extraneous navigation signals. The disadvantage of [15] is the impossibility of ensuring the synchronous operation of communication stations and satellite navigation systems.

In [16], it is proposed to improve the detection indicators of a stealth aerial vehicle at the expense of additional energy of extraneous signals of television communication. The disadvantage of [16] is the impossibility of ensuring synchronous operation of communication stations and digital television signal sources.

In [17], the signal/noise ratio was calculated with the simultaneous use of radar and a digital television signal. The disadvantage of [17] is due to the presence of an additional powerful continuous television signal in the additional reception channel.

In [18], the Loran-C navigation system (manufactured by the United States of America) is used to increase the conditional probability of correct detection of a stealth aerial vehicle. The disadvantage of [18] is the lack of possibility of using Loran-C system signals in a network of small-sized radars.

In [19], an assessment of the current state of radar technologies for the detection of unmanned aerial vehicles was carried out. The main attention in [19] is on MIMO methods and methods of beam formation of the antenna directional pattern. The disadvantage of [19] is the limited number of cases of detection of unmanned aerial vehicles under urban conditions at short distances.

In [20], a large number of methods for detecting aerial objects using MIMO radars were analyzed. It is noted that MIMO technology is developing rapidly. However, paper [20] does not analyze methods for the detection of stealth aerial vehicles by a network of small-sized radars.

In [21], the use of a wide-band multilateration system is considered. However, in [21] it is stated that such a system is ineffective in the case of detection of aerial objects by a network of small-sized radars.

In [22], the method for detecting and determining the coordinates of an aerial object using maximum likelihood estimates is considered. The disadvantage of [22] is the cumbersomeness of calculations, the solution of multidimensional optimization problems.

In [23], restrictions on the solution of the optimization problem by using only linear and quadratic functions are proposed. The disadvantage of [23] is the difficulty of its use in the case of detection of an aerial object by a network of small-sized radars.

In [24], the signal-to-noise ratio was calculated with the simultaneous use of radar and a sound signal from a stealth aerial vehicle. The disadvantage of [24] is the impossibility of providing synchronous processing of radar and sound signals.

In [25], a method for detecting an unmanned aerial object based on its acoustic signal is proposed. The disadvantage of [25] is the impossibility of combining the simultaneous processing of radar and acoustic signals in a network of small-sized radars.

In [26], a method of detecting an unmanned aerial vehicle by a small-sized multi-rotor radar is considered. The disadvantage of [26] is the specifics of building a small-sized radar for the detection of unmanned aerial vehicles of the multi-rotor type.

In [27] it is proposed to introduce changes in the design of the antenna system of radars for the detection of aerial objects. The calculation of the antenna system is carried out, the characteristics of its directional pattern, etc. are given. The disadvantage of [27] is the impossibility of using the method in a network of small-sized radars, the design of which cannot be changed.

Paper [28] proposed methods for improving the radar antenna system to enhance the detection quality of a stealth aerial vehicle. The disadvantage of [28] is the impossibility of using the method in a network of small-sized radars, the design of which cannot be changed.

Methods for building radars using MIMO technology are proposed in [29]. The disadvantage of [29] is that methods for detecting stealth aerial vehicles are not considered.

In [30], a method for building a MIMO radar system based on a genetic algorithm is proposed. The disadvantage of [30] is the practical complexity of implementing such a system construction method and the instability of genetic algorithms in general.

In [31], a network of two small-sized radars is considered and a method of detecting a stealth aerial vehicle in a network of two small-sized radars is proposed. The disadvantage of [31] is the limitation of using only methods of coherent signal processing, which is not always implemented in practice.

In [32], a network of two small-sized radars is considered and a method for detecting a stealth aerial vehicle in a network of two small-sized radars is proposed. At the same time, incoherent signal processing is considered. The disadvantage of [32] is the difficulty of determining the common viewing area of two small network radars, where a stealth aerial vehicle is detected.

Thus, in the network of two small-sized radars, stealth aerial vehicles are detected using known methods. Known methods do not take into account the peculiarities of building a network of small-sized radars, the complexity of their synchronization and reception of signals from other elements of the network. This, in turn, leads to a decrease in the quality of detection of stealth aerial vehicles.

Therefore, it is necessary to conduct further research on improving the method of detecting stealth aerial vehicles using a network of two small-sized radars with decentralized signal processing.

3. The aim and objectives of the study

The purpose of our study is to increase the conditional probability of correct detection of a stealth aerial vehicle by a network of two small-sized radars with decentralized signal processing. This will make it possible to improve the quality of detection of stealth aerial vehicles.

To achieve the goal, it is necessary to solve the following tasks:

– to outline main stages of the method for detecting stealth aerial vehicles using a network of two small-sized radars with decentralized signal processing;

– to evaluate the quality of detection of a stealth aerial vehicle by a network of two small-sized radars with decentralized signal processing.

4. The study materials and methods

The object of this study is the process of detecting stealth aerial vehicles by a network of two small-sized radars with decentralized signal processing. The main hypothesis of the study assumed that combining two small-sized radars into a network would improve the quality of detection of stealth aerial vehicles with decentralized signal processing.

The following research methods were used during the research:

– methods of system analysis;
– mathematical apparatus of matrix theory;
– methods of probability theory and mathematical statistics;
– methods of integral and differential calculus;
– iterative methods;
– radar location methods;
– methods of multi-position radar;
– methods of digital signal processing;
– methods of statistical theory of detection and measurement of parameters of radar signals;
– methods of mathematical modeling.

The following limitations and assumptions were accepted during the research:

– digital signal processing is carried out in small-sized radars;
– the term “stealth aerial vehicle” means an aerial object with a small value of the effective scattering surface;
– examples of objects with a small value of the effective scattering surface: cruise missiles, unmanned aerial vehicles, anti-radar missiles, etc., for example, [6, 7, 33];
– each radar can receive only its reflected signal from an aerial object;
– there is no possibility of receiving a signal reflected by the radar from an aerial object, the sounding signal of which is emitted by another radar;
– conditions for coherent processing of signals are not provided;
– there are no obstacles (artificial and natural);
– small-sized radars operate in the X-band of frequencies;
– inconspicuous air objects move with average speeds of 0.5–0.9 M;
– stealth aerial vehicles have an average effective scattering surface of up to 1 sq.m;
– to confirm the theoretical calculations, the method of Monte Carlo statistical tests was chosen.

The following means were used to confirm theoretical calculations and modeling:

– hardware: ASUSTeK COMPUTER INC model X550CC, 3rd Gen processor DRAM Controller – 0154, NVIDIA GeForce GT 720M;
– software: high-level programming language and interactive environment for programming, numerical calculations, and visualization of results MATLAB R2017b;
– software: high-level programming language Python 3.11.

5. Research results on the detection method with decentralized signal processing

5. 1. Main stages of the detection method with decentralized signal processing

Fig. 1 shows the network of two small-sized radars [12]. Radar positions are spatially dispersed. Information is processed at the central processing point. Such a processing point can be located separately or can be combined with one of the radars.

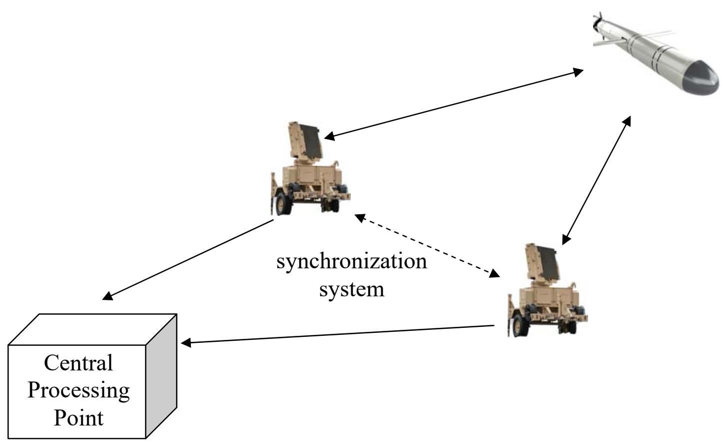

Fig. 1. A network of two small-sized radars with information processing at a central processing point [12]

When detecting signals by a network of two small-sized radars, we shall use the general theory of space-time signal processing, for example, [10, 15]. In accordance with [10, 15], the detection of a stealth aerial vehicle will be understood as the fact of the presence or absence of an aerial object in the radar discrimination element.

Probing signals are emitted in a network of two small-sized radars. At the same time, such signals must be orthogonal [31, 32]. Methods of ensuring orthogonality of signals are considered in known works, for example, [34, 35].

Therefore, probing signals are represented by expression (1) [31, 32]:

$$\frac{1}{2}\int_{-\infty}^{\infty} I_{0_1}(t) I^*_{0_2}(t)\,\mathrm{d}t = \begin{matrix} 0, i\neq j, \\ \tau_{э} i=j, \end{matrix}\; i,j=\overline{1,2}, \quad (1)$$

where $I_{0_1}(t)$, $I_{0_2}(t)$ are the complex normalized contours of sounding signals, respectively, of the first and second radars;

* – symbol of complex conjugation;

τ_i is the pulse duration.

Sounding orthogonal signals (expression (1)) are reflected from an aerial object. In the case when the size of a stealth aerial vehicle is much larger than a wavelength, there is a fluctuation in the signals received by each radar. At the same time, amplitude fluctuations are distributed according to Rayleigh's law, and phase fluctuations are uniformly distributed in the interval [−π; π] [10, 15]. In the case when the size of a stealth aerial vehicle is no more than a wavelength, there is no fluctuation in the signals received by each radar. Also in this case, friendly signal fluctuations are possible [10, 15].

The signal is received by each radar separately and only its own. We present these received signals in the form (2):

$$I_i\left(t,\vec{\lambda}_i\right) = I_{s_i} e^{\left(-j\varphi_{s_i}\right)} I_{0_i}\left(t-t_{s_i}\right) e^{\left(j(\omega_0+\Omega_{s_i})(t-t_{s_i})\right)}, \quad (2)$$

where I_{s_i} is the amplitude characteristic for the i-th signal (mathematical expectation of the amplitude);

$\vec{\lambda}_i$ – characteristics of the i-th signal parameters (vector of informative parameters).

In expression (2), notations are accepted (i=1 for the first network radar; i=2 for the second network radar). The vector of informative parameters is represented by expression (3):

$$\left(\varphi_{s_i}, t_{s_i}, \Omega_{s_i}, \omega_{0_i}\right), \quad (3)$$

where φ_{s_i} is the initial phase of the received signal for the i-th radar of the network; t_{s_i} – delay time of the received signal for the i-th radar of the network; Ω_{s_i} – Doppler frequency correction for the i-th radar of the network; ω_{0_i} – the carrier frequency of the received signal for the i-th radar of the network; $I_{0_i}\left(t-t_{s_i}\right)$ is the normalized envelope of the received signal for the ith radar of the network.

In expression (2), the normalized envelope of the received signal for the ith radar of the network $I_{0_i}\left(t-t_{s_i}\right)$ is determined by the modulation law.

In the case when each radar in the network receives and processes only its own signal, the likelihood ratio L according to the Neumann-Pearson test is represented by expression (4) [10, 15]:

$$L=\sum_{i=1}^{2}\left|\int_{-\infty}^{\infty} I^*_{0i}(t-t_0)x_i(t)dt\right|^2, \quad (4)$$

where $I^*_{0i}\left(t-t_0\right)$ is the impulse characteristic of the matched filter of the signal emitted by the i-th radar; $x_i(t)$ is the signal received by the i-th radar receiver.

Taking into account expression (4), the optimal signal detection algorithm according to the Neumann-Pearson criterion when each network radar receives only its own signal is represented by expression (5):

$$L=\sum_{i=1}^{2}\left|\int_{-\infty}^{\infty} I^*_{0i}(t-t_0)x_i(t)dt\right|^2 \begin{matrix}>\\ \leq\end{matrix} th, \quad (5)$$

where th is the detection threshold.

The detection threshold, taking into account [31, 32], is determined by the given conditional probability of a false alarm.

Considering expression (5), Fig. 2 shows the scheme of the signal detector optimal according to the Neumann-Pearson criterion in the case when each radar of the network receives only its own signal and centralized information processing is carried out.

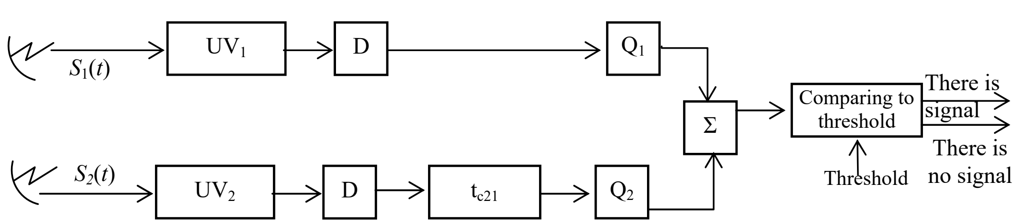

Fig. 2. Schematic diagram of the optimal signal detector according to the Neumann-Pearson criterion in the case when each radar of the network receives only its own signal, with centralized information processing

Therefore, taking into account expression (5) and Fig. 2, the main stages of the method (sequence of actions) for detecting a stealth aerial vehicle in the case when each radar of the network receives only its own signal and centralized information processing is carried out, are as follows:

– each radar emits its own sounding signal. These received sounding signals are output. The output signals are represented by expression (2). In the presence of an aerial object, the sounding signal is reflected from the object and propagates in the direction of the radar. This is a condition for moving to the next stage;

– each radar receives only its own signal reflected from a stealth aerial vehicle. If the signal is successfully received by each radar, the transition to the next stage is made;

– coordinated filtering in the receiving system of each radar of its signal. Matched filtering refers to the processing of received signals against a background of white noise by a filter. At the same time, the impulse characteristic of the filter is consistent with the expected signal. If the pulse characteristics are consistent, the transition to the next stage is made;

– quadratic detection in each radar of its signal at the output of its matched filter. Quadratic detection is a non-linear operation that is the inverse of amplitude modulation. An amplitude-modulated signal is received at the input of the detector, and a low-frequency signal voltage is received at the output of the detector;

– finding the sum of detected signals in each radar at the output of its matched filter;

– formation for each range element of incoherent summation of signals from two network radars with random and independent radiation phases;

– comparison of the incoherent sum of signals from two radars with threshold *th*;

– when the incoherent sum of the threshold value *th* is exceeded, a decision is made about the presence of an aerial object in a certain element of the range. Otherwise, a decision is made about the absence of an aerial object in a certain element of the range.

The scheme of the signal detector, optimal according to the Neumann-Pearson criterion, in the case when each radar of the network receives only its own signal, which is shown in Fig. 2, provides for centralized processing of information. Under real conditions, it is not always possible to ensure centralized processing of information.

Therefore, the case of decentralized information processing is considered. Decentralized information processing involves the following:

– preliminary detection of the signal is carried out by each radar separately;

– in each range element, the signal is compared with the threshold level;

– when the threshold level in the range element is exceeded, the value of one is assigned to such range element;

– if the threshold level in the range element is not exceeded, the value of zero is assigned to such range element;

– the sequence of zeros and ones obtained in this way in each radar of the network is transmitted to the central processing point (Fig. 1);

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element. Such a decision is made based on the results of the combined processing of binary sequences coming from the radars according to the "*k* out of *m*" criterion.

The scheme of the optimal signal detector according to the Neumann-Pearson criterion in the case when each radar of the network receives only its own signal and with decentralized information processing is shown in Fig. 3.

Thus, the improved method for detecting stealth aerial vehicles by a network of two small-sized radars with decentralized information processing involves the following:

– each radar emits its own probing signal;

– each radar receives only its own signal reflected from a stealth aerial vehicle;

– coordinated filtering in the reception system of each radar of its signal;

– quadratic detection in each radar of its signal at the output of its matched filter;

– finding the sum of detected signals in each radar at the output of its matched filter;

– preliminary detection of the signal is carried out by each radar separately;

– in each range element, the signal is compared with the threshold level;

– when the threshold level in the range element is exceeded, the value of one is assigned to such range element;

– if the threshold level in the range element is not exceeded, the value of zero is assigned to such range element;

– the sequence of zeros and ones obtained in this way in each radar of the network is transmitted to the central processing point;

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element. Such a decision is made based on the results of the combined processing of binary sequences coming from the radars according to the "*k* out of *m*" criterion.

It should be noted that the implementation of the improved method for detection of stealth aerial vehicles by a network of two small-sized radars with decentralized information processing does not require mutual coherence of the received signals at the network radar inputs.

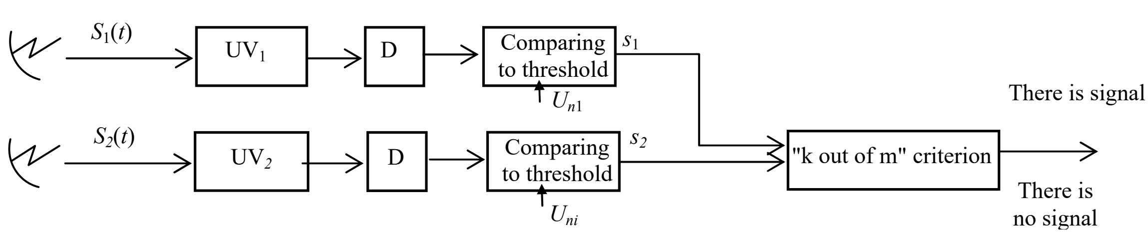

Fig. 3. Scheme of the optimal Neumann-Pearson signal detector in the case when each network radar receives only its own signal, with decentralized information processing

5. 2. Evaluation of the detection quality of a stealth aerial vehicle during decentralized signal processing

It is known [31, 32] that the quality of signal processing in a network of two small-sized radars is estimated by the conditional probability of correct detection.

The output statistics for the detection of a stealth aerial vehicle by a network of two small-sized radars during decentralized signal processing in the absence of a signal are calculated according to expression (6):

$$L_0=\sum_{i=1}^{2}\left|\int_{-\infty}^{\infty} I_{0_i}^{*}(t-t_0)n_i(t)\mathrm{d}t\right|^2=\sum_{i=1}^{2}\left|Z_{0i}\right|^2, \tag{6}$$

where $Z_{0i}=\int_{-\infty}^{\infty} I_{i0}^{*}(t-t_0)n_i(t)\mathrm{d}t$ is the correlation integral in the absence of a received signal; $n_i(t)$ is the noise function in the ith small-sized radar.

Statistics (6) when detecting a stealth aerial vehicle by a network of two small-sized radars during decentralized signal processing in the absence of a signal is the sum of M squares of independent Gaussian values with zero mean and equal variances. Such statistics are described by a central χ^2 (chi-square) distribution with M degrees of freedom.

The output statistics for the detection of a stealth aerial vehicle by a network of two small-sized radars during decentralized signal processing in the presence of a signal are calculated according to expression (7):

$$L_1=\sum_{i=1}^{2}\left|\int_{-\infty}^{\infty} I_{0i}^{*}(t-t_0)\left(x_i(t)+n_i(t)\right)\mathrm{d}t\right|^2=\sum_{i=1}^{2}\left|Z_{1i}\right|^2, \tag{7}$$

where $Z_{1i}=\int_{-\infty}^{\infty} I_{i0}^{*}(t-t_0)\left(x_i(t)+n_i(t)\right)\mathrm{d}t$ is the correlation integral in the presence of a received signal.

To calculate the conditional probability of correct detection, we shall use the results of [32]. Taking into account [32], the conditional probability of correct detection is calculated according to expression (8):

$$D=\exp\left(-\frac{th}{1+q^2}\right)\sum_{k=1}^{2}\left(\frac{\left(\frac{th}{2}\right)^2}{k!\left(1+q^2\right)^k}\right). \tag{8}$$

Also, taking into account [32], at a fixed value of the conditional probability of a false alarm, the detection threshold th is determined from expression (9):

$$F=\exp\left(-\frac{th}{1+q^2}\right)\sum_{k=1}^{2}\left(\frac{\left(\frac{th}{2}\right)^2}{k!}\right). \tag{9}$$

The relationship between the signal-to-noise ratio for an autonomous radar and two small-sized radars that are connected in a network is represented by expression (10) [31, 32]:

$$\overline{q_{\Sigma}^2}=4q_s^2, \tag{10}$$

where $\overline{q_{\Sigma}^2}$ is the signal/noise ratio of two small-sized radars connected to the network; q_s^2 – signal/noise ratio for an autonomous radar.

To assess the quality of aerial object detection, the conditional probability of correct detection of stealth aerial vehicles by a network of two small-sized radars with decentralized information processing was calculated. In this case, expression (8) was used. The value of the detection threshold is calculated according to expression (9) at a fixed value of the conditional probability of a false alarm.

A comparison of the quality of detection by the improved method of detecting stealth aerial vehicles by a network of two small-sized radars during decentralized information processing with the known method was carried out. As a well-known method, the method of detecting an aerial object with one radar was chosen [9, 31].

For comparison with the known method, the conditional probability of correct detection when using one radar was calculated. The conditional probability of correct detection was calculated according to expression (11) [31, 32]:

$$D=F^{\frac{1}{\left(1+q_s^2\right)}}. \tag{11}$$

The detection curves of a stealth aerial vehicle are shown in Fig. 4. In the calculations, it is assumed that the conditional probability of a false alarm is $F=10^{-6}$.

In Fig. 4, the detection curve (dependence of the conditional probability of correct detection on the signal/noise ratio) of a stealth aerial vehicle by one radar is represented in green. The conditional probability of correct detection was calculated using expression (11). The detection curve (the dependence of the conditional probability of correct detection on the signal/noise ratio) of a stealth aerial vehicle by a network of two small-sized radars during decentralized information processing is shown in yellow. The conditional probability of correct detection was calculated using expression (8).

From the analysis of Fig. 4, it can be seen that when a stealth aerial vehicle is detected by a network of two small-sized radars, decentralized information processing provides a higher value of the conditional probability of correct detection by (19–26) % on average.

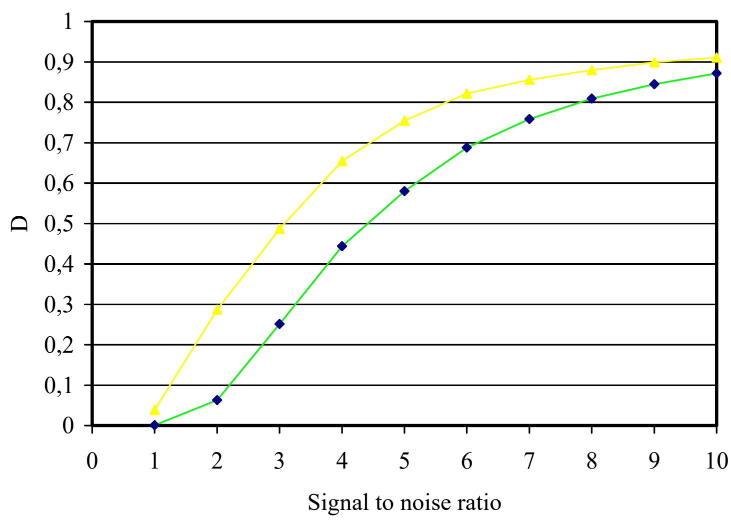

Fig. 4. Detection curves of a stealth aerial vehicle by one radar (green curve) and a network of two small-sized radars with decentralized information processing (yellow curve)

The analysis of Fig. 4 also reveals that the quality of detection of signals by a network of two small-sized radars with decentralized information processing is equivalent to the quality of detection with incoherent signal processing. At the same time, at small values of the signal/noise ratio, the gain is still greater.

6. Discussion of the research results regarding the improvement of the method for detection in decentralized processing

A network of two small-sized radars with information processing at the central processing point has been considered. The expression for the likelihood ratio according to the Neumann-Pearson test when detecting signals by a network of two radars, when each radar receives only its signal (expression (4)) is obtained. A signal detection algorithm, optimal according to the Neumann-Pearson criterion, was obtained when each network radar receives only its own signal (expression (5)).

The scheme of the signal detector, optimal according to the Neumann-Pearson criterion, is shown in the case when each radar of the network receives only its own signal and centralized information processing is carried out (Fig. 2). The main stages of the method for detecting a stealth aerial vehicle in the case when each radar of the network receives only its signal and centralized information processing are given. Namely:

– each radar emits its own probing signal;

– each radar receives only its own signal reflected from a stealth aerial vehicle;

– coordinated filtering in the reception system of each radar of its signal;

– quadratic detection in each radar of its signal at the output of its matched filter;

– finding the sum of detected signals in each radar at the output of its matched filter;

– formation for each range element of incoherent summation of signals from two network radars with random and independent radiation phases.

The case of decentralized information processing has been considered. Decentralized information processing involves the following:

– preliminary detection of the signal is carried out by each radar separately;

– in each range element, the signal is compared with the threshold level;

– when the threshold level in the range element is exceeded, the value of one is assigned to such range element;

– if the threshold level in the range element is not exceeded, the value of zero is assigned to such range element;

– the sequence of zeros and ones obtained in this way in each radar of the network is transmitted to the central processing point (Fig. 1);

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element. Such a decision is made based on the results of the combined processing of binary sequences coming from the radars according to the "*k* out of *m*" criterion.

The scheme of the signal detector, optimal according to the Neumann-Pearson criterion, is given in the case when each radar of the network receives only its own signal, and with decentralized information processing (Fig. 3).

Thus, the improved method for detecting stealth aerial vehicles by a network of two small-sized radars with decentralized information processing, unlike the known ones (for example, [10, 11, 31, 32]), involves the following:

– each radar emits its own probing signal;

– each radar receives only its own signal reflected from a stealth aerial vehicle;

– coordinated filtering in the reception system of each radar of its signal;

– quadratic detection in each radar of its signal at the output of its matched filter;

– finding the sum of detected signals in each radar at the output of its matched filter;

– preliminary detection of the signal is carried out by each radar separately;

– in each range element, the signal is compared with the threshold level;

– when the threshold level in the range element is exceeded, the value of one is assigned to such range element;

– if the threshold level in the range element is not exceeded, the value of zero is assigned to such range element;

– the sequence of zeros and ones obtained in this way in each radar of the network is transmitted to the central processing point;

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element. Such a decision is made based on the results of the combined processing of binary sequences coming from the radars according to the "*k* out of *m*" criterion.

It should be noted that the implementation of the improved method for detection of stealth aerial vehicles by a network of two small-sized radars with decentralized information processing does not require mutual coherence of the received signals at the network radar inputs.

The quality of detection of a stealth aerial vehicle by a network of two small-sized radars with decentralized signal processing was evaluated. In Fig. 4, the detection curve (dependence of the conditional probability of correct detection on the signal/noise ratio) of a stealth aerial vehicle by one radar is represented in green. The detection curve (the dependence of the conditional probability of correct detection on the signal/noise ratio) of a stealth aerial vehicle by a network of two small-sized radars during decentralized information processing is shown in yellow. From the analysis of Fig. 4, it can be seen that when a stealth aerial vehicle is detected by a network of two small-sized radars, decentralized information processing provides a higher value of the conditional probability of correct detection by (19–26) % on average.

The analysis of Fig. 4 also reveals that the quality of detection of signals by a network of two small-sized radars with decentralized information processing is equivalent to the quality of detection with incoherent signal processing. At the same time, at small values of the signal/noise ratio, the gain is still greater.

This study has the following main limitations:

– mandatory presence of digital channels for signal processing in small-sized radars;

– absence of influence of natural and artificial obstacles.

The disadvantage of the method for detecting a stealth aerial vehicle using a network of two small-sized radars is its efficiency only with decentralized information processing.

Further research should focus on the investigation of the geometry of the construction of a network of small-sized radars.

7. Conclusions

1. A method for detecting a stealth aerial vehicle by a network of two small-sized radars with decentralized processing has been improved. The features of the stages of the proposed method, unlike the known ones, are:

– each radar receives only its own signal reflected from a stealth aerial vehicle;

– coordinated filtering, quadratic detection, finding the sum of detected signals, signal detection is carried out separately by each radar;

– at the central processing point, a decision is made about the presence or absence of a stealth aerial vehicle in the range element based on the results of the combined processing of the binary sequences coming from the radars, according to the "*k* out of *m*" criterion.

2. Evaluation of the detection quality of a stealth aerial vehicle by a network of two small-sized radars with decentralized signal processing was carried out. It was established that when detecting a stealth aerial vehicle by a network of two small-sized radars, decentralized information processing provides a higher value of the conditional probability of correct detection, by (19–26) % on average. The quality of detection of signals by a network of two small-sized radars with decentralized information processing is equivalent to the quality of detection with incoherent signal processing. At the same time, at small values of the signal/noise ratio, the gain is still greater.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Sentinel Radar. Available at: https://www.rtx.com/raytheon/what-we-do/land/sentinel-radar
2. NASAMS anti-aircraft missile system. Available at: https://en.missilery.info/missile/nasams
3. Carafano, J. J. Rapid advancements in military tech. Available at: https://www.gisreportsonline.com/r/military-technology/
4. Erl, J. (2022). Sensing digital objects in the air: Ultraleap introduces new technology. Available at: https://mixed-news.com/en/sensing-digital-objects-in-the-air-ultraleap-introduces-new-technology/
5. US Sentinel Radar Was Recorded in Ukraine. Available at: https://en.defence-ua.com/weapon_and_tech/us_sentinel_radar_was_recorded_in_ukraine-3357.html
6. Kalibr. Naval Cruise missile family. Available at: https://www.militarytoday.com/missiles/kalibr.htm
7. Orlan-10 Uncrewed Aerial Vehicle (UAV). Available at: https://www.airforce-technology.com/projects/orlan-10-unmanned-aerial-vehicle-uav/#catfish
8. Bezouwen, J., Brandfass, M. (2017). Technology Trends for Future Radar. Available at: https://www.microwavejournal.com/articles/29367-technology-trends-for-future-radar
9. Richards, M. A., Scheer, J. A., Holm, W. A. (Eds.) (2010). Principles of Modern Radar: Basic principles. Institution of Engineering and Technology. https://doi.org/10.1049/sbra021e
10. Chernyak, V. (2014). Signal detection with MIMO radars. Uspehi sovremennoj radiojelectroniki, 7, 35–48.
11. Lishchenko, V., Kalimulin, T., Khizhnyak, I., Khudov, H. (2018). The Method of the organization Coordinated Work for Air Surveillance in MIMO Radar. 2018 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo). https://doi.org/10.1109/ukrmico43733.2018.9047560
12. Khudov, H. (2020). The Coherent Signals Processing Method in the Multiradar System of the Same Type Two-coordinate Surveillance Radars with Mechanical Azimuthal Rotation. International Journal of Emerging Trends in Engineering Research, 8 (6), 2624–2630. https://doi.org/10.30534/ijeter/2020/66862020
13. Neyt, X., Raout, J., Kubica, M., Kubica, V., Roques, S., Acheroy, M., Verly, J. G. (2006). Feasibility of STAP for Passive GSM-Based Radar. 2006 IEEE Conference on Radar. https://doi.org/10.1109/radar.2006.1631853
14. Multilateration (MLAT) Concept of Use. Edition 1.0 (2007). ICAO Asia and Pacific Office. Available at: https://www.icao.int/APAC/Documents/edocs/mlat_concept.pdf
15. Willis, N. J. (2004). Bistatic Radar. Institution of Engineering and Technology. https://doi.org/10.1049/sbra003e
16. Lishchenko, V., Khudov, H., Tiutiunnyk, V., Kuprii, V., Zots, F., Misiyuk, G. (2019). The Method of Increasing the Detection Range of Unmanned Aerial Vehicles In Multiradar Systems Based on Surveillance Radars. 2019 IEEE 39th International Conference on Electronics and Nanotechnology (ELNANO). https://doi.org/10.1109/elnano.2019.8783263
17. Ruban, I., Khudov, H., Lishchenko, V., Pukhovyi, O., Popov, S., Kolos, R. et al. (2020). Assessing the detection zones of radar stations with the additional use of radiation from external sources. Eastern-European Journal of Enterprise Technologies, 6 (9 (108)), 6–17. https://doi.org/10.15587/1729-4061.2020.216118

18. LORAN-C. Available at: https://skybrary.aero/articles/loran-c
19. Rojhani, N., Shaker, G. (2024). Comprehensive Review: Effectiveness of MIMO and Beamforming Technologies in Detecting Low RCS UAVs. Remote Sensing, 16 (6), 1016. https://doi.org/10.3390/rs16061016
20. Kalkan, Y. (2024). 20 Years of MIMO Radar. IEEE Aerospace and Electronic Systems Magazine, 39 (3), 28–35. https://doi.org/10.1109/maes.2023.3349228
21. Neven, W. H., Quilter, T. J., Weedon, R., Hogendoorn, R. A. (2005). Wide Area Multilateration Wide Area Multilateration. Report on EATMP TRS 131/04. Version 1.1. NLR. Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf
22. Mantilla-Gaviria, I. A., Leonardi, M., Balbastre-Tejedor, J. V., de los Reyes, E. (2013). On the application of singular value decomposition and Tikhonov regularization to ill-posed problems in hyperbolic passive location. Mathematical and Computer Modelling, 57 (7-8), 1999–2008. https://doi.org/10.1016/j.mcm.2012.03.004
23. Schau, H., Robinson, A. (1987). Passive source localization employing intersecting spherical surfaces from time-of-arrival differences. IEEE Transactions on Acoustics, Speech, and Signal Processing, 35 (8), 1223–1225. https://doi.org/10.1109/tassp.1987.1165266
24. Ryu, H., Wee, I., Kim, T., Shim, D. H. (2020). Heterogeneous sensor fusion based omnidirectional object detection. 2020 20th International Conference on Control, Automation and Systems (ICCAS). https://doi.org/10.23919/iccas50221.2020.9268431
25. Salman, S., Mir, J., Farooq, M. T., Malik, A. N., Haleemdeen, R. (2021). Machine Learning Inspired Efficient Audio Drone Detection using Acoustic Features. 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST). https://doi.org/10.1109/ibcast51254.2021.9393232
26. Liu, Y., Yi, J., Wan, X., Cheng, F., Rao, Y., Gong, Z. (2018). Experimental Research on Micro-Doppler Effect of Multi-rotor Drone with Digital Television Based Passive Radar. Journal of Radars, 7 (5), 585–592. https://doi.org/10.12000/JR18062
27. Wang, W. (2016). Overview of frequency diverse array in radar and navigation applications. IET Radar, Sonar & Navigation, 10 (6), 1001–1012. https://doi.org/10.1049/iet-rsn.2015.0464
28. Li, J., Stoica, P. (Eds.) (2008). MIMO Radar Signal Processing. John Wiley & Sons. https://doi.org/10.1002/9780470391488
29. Li, Y. (2021). MIMO Radar Waveform Design: An Overview. Journal of Beijing Institute of Technology, 30 (1), 44–59. https://doi.org/10.15918/j.jbit1004-0579.2021.002
30. Oleksenko, O., Khudov, H., Petrenko, K., Horobets, Y., Kolianda, V., Kuchuk, N. et al. (2021). The Development of the Method of Radar Observation System Construction of the Airspace on the Basis of Genetic Algorithm. International Journal of Emerging Technology and Advanced Engineering, 11 (8), 23–30. https://doi.org/10.46338/ijetae0821_04
31. Khudov, H., Berezhnyi, A., Yarosh, S., Oleksenko, O., Khomik, M., Yuzova, I. et al. (2023). Improving a method for detecting and measuring coordinates of a stealth aerial vehicle by a network of two small-sized radars. Eastern-European Journal of Enterprise Technologies, 6 (9 (126)), 6–13. https://doi.org/10.15587/1729-4061.2023.293276
32. Khudov, H., Yarosh, S., Kostyria, O., Oleksenko, O., Khomik, M., Zvonko, A. et al. (2024). Improving a method for non-coherent processing of signals by a network of two small-sized radars for detecting a stealth unmanned aerial vehicle. Eastern-European Journal of Enterprise Technologies, 1 (9 (127)), 6–13. https://doi.org/10.15587/1729-4061.2024.298598
33. Chang, L. ZALA Lancet. Loitering munition. Available at: https://www.militarytoday.com/aircraft/lancet.htm
34. Shin, S. -J. (2017). Radar measurement accuracy associated with target RCS fluctuation. Electronics Letters, 53 (11), 750–752. https://doi.org/10.1049/el.2017.0901
35. Kishk, A., Chen, X. (Eds.) (2023). MIMO Communications - Fundamental Theory, Propagation Channels, and Antenna Systems. IntechOpen. https://doi.org/10.5772/intechopen.110927