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DETERMINING THE NUMBER OF SMALL-SIZED RADARS IN A NETWORK WITH COHERENT SIGNAL PROCESSING FOR THE DETECTION OF STEALTH AERIAL VEHICLES

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The object of this study is the process of determining the number of small-sized radars in the network when detecting stealth unmanned aerial vehicles. The main hypothesis of the study assumed that determining the optimal number of small-sized radars in the network will make it possible not to waste unnecessary resources of radars to detect stealth unmanned aerial vehicles.

The main stages of detection of a stealth unmanned aerial vehicle by a network of small-sized radars are:

– reception of the signal reflected from a stealth unmanned aerial vehicle by all small-sized radars of the network;

– coordinated filtering of incoming signals in each small-sized radar;

– compensation of phase shifts in each matched filter;

– coherent addition of output signals from each matched filter at the output of the receivers of each of the N small-sized radars performing reception;

– formation of a complex bypass at the output of the corresponding Doppler channel in each small-sized radar of the network;

– coherent processing of signals from all elements of the network of small-sized radars;

– detection of the output signal from the adder of coherent signals. At the same time, compensation for the random initial phase of signals reflected from a stealth unmanned aerial vehicle is also performed.

It has been established that the increase in the elements of the network of small-sized radars increases the value of the conditional probability of correct detection. Such an increase is more significant when the number of elements in the network of small-sized radars is increased to two or three. The gain in the signal/noise ratio when adding elements to the network of small-sized radars was evaluated. It was established that the optimal number of small-sized radars in a network with coherent signal processing when detecting stealth unmanned aerial vehicles is 2–3 radars

Keywords: small-sized radar, aerial object detection, number of network elements, conditional probability of correct detection

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1. Introduction

Recent technological advances in the field of reducing radar visibility have led to the appearance of stealth unmanned aerial vehicles [1]. Such stealth unmanned aerial vehicles create unprecedented opportunities for their application. On the other hand, new threats arise when using them. These can be threats related to terrorist attacks, espionage, smuggling, intelligence, etc. [2].

Small-sized radars are an effective means of detecting such stealth unmanned aerial vehicles [3, 4]. Small-sized radars are understood in the work as the radar intended for conducting radar reconnaissance of the air space. Control of a small-sized radar is carried out, as a rule, remotely. The compact radar operates in the X-band and has a phased array antenna. The small-sized radar is capable of detecting stealth unmanned aerial vehicles at ranges of up to 70–80 km and at altitudes from 20 to 5,000 meters. The use of mobile radars is due, first of all, to their mobility and relatively low weight. On the other hand, the small size of such radars causes a certain decrease in the quality indicators of detection of stealth unmanned aerial vehicles [5].

An effective way to improve the quality of detection of stealth unmanned aerial vehicles by small-sized radars is to combine them into multi-radar networks, for example [6, 7]. The elements of the network are directly small-sized radars.

The theoretical foundations of building multiradar networks are described, for example, in [8]. Applied questions of building multi-radar networks were mainly limited to general questions and considered the operation of networks with two or three small-sized radars. The issue of determining the optimal number of elements in a multi-radar network has not been fully investigated, especially with regard to small-sized radars.

Therefore, determining the number of small-sized radars in a multi-radar network when detecting stealth unmanned aerial vehicles is an urgent task.

2. Literature review and problem statement

In [6], the complication of the sounding signal structure in a separate small-sized radar is proposed. The disadvantage of [6] is the need to change the parameters of the radar transmitter, which is practically impossible. The impossibility of change is due to the need to make changes to the radar transmitter. Making such changes completely changes the purpose of such a radar.

In [7], the use of an antenna with a narrow directional pattern is proposed. This is practically impossible in small-sized radars. This is the main drawback of [7]. The use of antennas with a narrow directional pattern is due to the small dimensions of the radar. Narrowing the directional pattern is possible only by physically increasing the dimensions of the antenna system.

In [8], a general theory of building radar networks was developed. At the same time, the main attention is paid to all-round radars. However, practical issues of using multiradar networks are not considered in [8]. In addition, paper [8] does not consider the construction of multi-radar networks based on small-sized radars. Therefore, the theoretical methods of construction mainly do not take into account the peculiarities of the practical implementation of the process of detecting a stealth unmanned aerial vehicle by a network of small-sized radars.

In [9], the construction of a multi-radar network for the detection of aerial objects is proposed. At the same time, such a network uses the Multiple Input – Multiple Output (MIMO) principle. The disadvantage of [9] is the difficulty of applying the obtained results for small-sized radars. This is due to the fact that the MIMO principle in [9] is proposed for a certain class of radars, namely, large stationary radars with a long detection range.

In [10], by analogy with [9], the construction of a multi-radar network for the detection of aerial objects based on the MIMO principle is proposed. In contrast to [9], in [10] radars with mechanical rotation were used as network elements. Such radars with mechanical rotation are bulky due to the need to use a complex and bulky system of mechanical rotation of the antenna system.

In [11], the use of multiradar systems, which are built according to the multilateration principle, is proposed. Such systems were called multilateration systems. The disadvantage of [11] is the impossibility of applying the multilateration principle to multiradar systems based on small-sized radars. This is due to the relatively short range of the proposed multilateration systems.

In [12], it is proposed to additionally use the Loran-C navigation system (manufactured by the United States of America) with the all-round radar. The disadvantage of [12] is the difficulty of simultaneously using small-sized radars and signals of the Loran-C system. Such complexity is due to the need to synchronize the survey of the circular survey radars and the Loran-C navigation system.

In [13], the use of MIMO methods was proposed when combining specialized radars into a network for detecting unmanned aerial vehicles. At the same time, in [13], only the methods of forming directional diagrams of radar network elements are considered. The disadvantage of [13] is the limitation of using only specialized radars for the detection of unmanned aerial vehicles in the network. The impossibility of implementing the results from [9] is due to the specificity of the construction of radars for the detection of unmanned aerial vehicles of a certain class.

In [14], a theoretical analysis of the application of MIMO technology for the detection of aerial objects is given. The advantages and disadvantages of these methods are analyzed. However, in [14] the main attention is paid to the use of radars with a circular view. Such radars with mechanical rotation are bulky due to the need to use a complex and bulky system of mechanical rotation of the antenna system. At the same time, the number of such radars is not optimized.

A broadband multilateration system is proposed in [15]. Such a system is effective in controlling the movement of objects in the vicinity of civil airports at short distances (hundreds of meters). The methods from [15] are ineffective for use in a network of small-sized radars. This is due to the short range of the proposed broadband multilateration system.

In [16], a method for detecting aerial objects is proposed, which implements the algorithm of estimates with maximum likelihood. The use of [16] is related to its bulkiness, which makes its use in radar networks impossible. This is due to the theoretical orientation of [16] and complicated practical implementation in a network of small-sized radars.

In [17], it is proposed to use linear and quadratic functions for detecting an aerial object and determining the likelihood ratio. The disadvantage of [17] is that the proposed detection method does not take into account the specifics of building a network of small-sized radars. The impossibility of implementing [17] is due to a specific calculation of the likelihood ratio. Such a calculation makes it impossible to use linear and quadratic functions.

In [18], the combination of radars and sound sensors from an aerial object into a network is proposed. The material in [18] is represented only at the theoretical level without taking into account the practical possibility of its implementation. This complexity is due to the need to synchronize the radar survey and the area of operation of the sound sensors.

A method similar to [18] is also proposed in [19]. At the same time, the possibility of combining radar and acoustic signals is considered. Work [19] also has theoretical significance and certain difficulties regarding practical implementation. This complexity is due to the need to synchronize radar and acoustic signals.

In [20], the quality of detection of aerial objects in a network of two radars is improved by changing (improving) antenna systems of network elements. The disadvantage of [20] is the difficulty of practical implementation of making such changes, especially during the constant operation of radars. The impossibility of changing (improving) antenna systems is due to the need to make changes in the design of antenna systems. Making such changes completely changes the purpose of such a radar.

In [21], the main focus is on theoretical methods of MIMO technology. The disadvantage of [21] is the purely theoretical orientation of the work and the difficulty of practical implementation of the proposed methods in a network of two radars. This is due to the fact that the theoretical methods of the MIMO technology do not take into account the peculiarities of the practical implementation of the process of detecting a stealth unmanned aerial vehicle by a network of small-sized radars.

Paper [22] proposed the construction of a radar network using a genetic algorithm. The disadvantage of [22] is the use of an undefined number of radars in the network, the cumbersomeness of calculations, etc. This is due to the complexity of solving the optimization problem using genetic algorithms, the complexity of constructing and presenting the target function. Therefore, work [22] has a more theoretical value and does not take into account the peculiarities of the practical implementation of the process of detecting a stealth unmanned aerial vehicle by a network of small-sized radars.

In [23], the use of a network of small-sized radars for the detection of aerial objects is proposed. At the same time, coherent processing of signals in the network radars is used. The disadvantage of [23] is the use of a network of only two small-sized radars, a larger number of radars is not considered. Using a network of only two radars does not allow the generalization of the obtained results for a network with more than two radars.

In [24], by analogy with [23], the use of a network of small-sized radars for the detection of aerial objects is proposed. At the same time, incoherent processing of signals in network radars is used. The disadvantage of [24] is the use of a network of only two small-sized radars, a larger number of radars is not considered. The use of a network of only two radars does not allow the generalization of the obtained results for a network with more than two radars.

Thus, it was established that the construction of a network of small-sized radars increases the quality of detection of stealth unmanned aerial vehicles. But in most of the works cited above, the necessary number of radars in such a network is not defined. An exception is [23, 24], in which the number of radars in the network is determined, which is equal to two. But in practice, in many cases, the number of radars in the network is more than two.

Therefore, it is necessary to carry out further research on determining the number of small-sized radars in the network when detecting stealth unmanned aerial vehicles.

3. The aim and objectives of the study

The purpose of our study is to determine the number of small-sized radars in the network when detecting stealth unmanned aerial vehicles. This will make it possible not to waste unnecessary radar resources to detect stealth unmanned aerial vehicles.

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

– to outline the main stages and scheme of detection of stealth unmanned aerial vehicles in the network of small-sized radars;

– to evaluate the gain in the signal/noise ratio when adding elements to the network of small-sized radars.

4. The study materials and methods

The object of our study is the process of determining the number of small-sized radars in the network when detecting stealth unmanned aerial vehicles. The main hypothesis of the study assumed that the determination of the optimal number of small-sized radars in the network for the detection of stealth unmanned aerial vehicles would make it possible not to waste unnecessary resources of radars for the detection of stealth unmanned aerial vehicles.

The following research methods were used during our study:

– methods of multi-position radar;

– methods of digital signal processing;

– methods of probability theory and mathematical statistics;

– methods of integral and differential calculus;

– methods of system analysis;

– mathematical apparatus of matrix theory;

– methods of statistical theory of detection and measurement of parameters of radar signals;

– iterative methods;

– methods of mathematical modeling.

The following limitations and assumptions were adopted during the research:

– small-sized radars are digital, that is, digital devices are used for signal processing;

– similarly to [23, 24], stealth unmanned aerial vehicles are considered to be objects with an insignificant value of the effective scattering surface (unmanned aerial vehicles, anti-radar missiles, cruise missiles, etc., for example, [8, 9, 25]);

– the number of radars in the network is equal to *M*;

– each radar can receive a reflected signal from an aerial object emitted by this particular radar and other radars;

– the condition of mutual orthogonality of probing signals is fulfilled;

– coherent processing of signals is carried out;

– conditions for coherent signal processing are provided;

– the influence of obstacles is not taken into account;

– range of operating frequencies of small-sized radars – X-band;

– the speed of movement of inconspicuous air objects is subsonic;

– effective scattering surface of inconspicuous air objects – up to 1 sq.m;

– when conducting simulations, the main method is the Monte Carlo statistical test method.

Theoretical calculations were confirmed by simulation. To this end, we used:

– software: high-level programming language and interactive environment for programming, numerical calculations, and visualization of results MATLAB R2017b;

– hardware: ASUSTeK COMPUTER INC model X550CC, 3rd Gen processor DRAM Controller – 0154, NVIDIA GeForce GT 720M.

5. Results of the study on determining the number of small-sized radars

5. 1. Main stages and scheme of detection of stealth unmanned aerial vehicles

To present the material, we shall use the results reported in [23]. Summarizing the results from [23], it was determined that the probing signal is represented by expression (1):

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

where $I_{0_i}(t)$, $I_{0_j}(t)$ are the contours of probing signals emitted by *i*-th and *j*-th small-sized radars;

τ_i – pulse duration;

M is the number of small radars in the network;

* is a symbol of complex conjugation.

After the sounding signal is emitted by each small-sized radar, they switch to the receiving mode. At the same time, each small-sized radar has the ability to receive its signal and reflected signals from stealth unmanned aerial vehicles due to probing by other mobile radars. Mathematically, this is represented by expression (2):

$$I^*(t,\vec{\lambda}) = \left(I_1^*(t,\vec{\lambda}_1), I_2^*(t,\vec{\lambda}_2), \ldots, I_i^*(t,\vec{\lambda}_i), \ldots, I_M^*(t,\vec{\lambda}_M)\right), \tag{2}$$

where $I(t,\vec{\lambda})$ is the set of echo signals from all small-sized radars of the network;

$I_i(t,\vec{\lambda}_i)$ is the echo signal of the *i*th small-sized radar.

Echo signals $I_i(t,\vec{\lambda}_i)$ of the *i*th (*i*=1, 2..., *i*,...*M*) small-sized radar are represented by expression (3) [23]:

$$I_i(t,\vec{\lambda}_i) = I_{s_i} e^{(-j\varphi_{s_i})} I_{0_i}(t - t_{s_i}) e^{\left(j(\omega_0 + \Omega_{s_i})(t - t_{s\,i})\right)}, \tag{3}$$

where I_{s_i} is the mathematical expectation; $\vec{\lambda}_i$ – informative parameters of the signal in the *i*th small-sized radar. These informative parameters are represented by a vector $(\varphi_{s_i}, t_{s_i}, \Omega_{s_i}, \omega_{0_i})$; φ_{s_i} – the initial phase of the signal in the *i*th small-sized radar; t_{s_i} – signal delay time in the *i*th small-sized radar; Ω_{s_i} – Doppler frequency correction in the *i*th small-sized radar; ω_{0_i} is the carrier frequency of the signal in the *i*th small-sized radar; $I_{0_i}(t - t_{s_i})$ is the envelope of the signal in the *i*th small-sized radar. This envelope is complex and normalized and is determined by the modulation law in the *i*th small-sized radar.

Also, generalizing the results from [23] for the case when the network consists of *M* small-sized radars, we obtain the following. Taking into account the conditions of coherent processing from a stealth unmanned aerial vehicle, the optimal detection algorithm is determined. At the same time, we shall use the well-known Neumann-Pearson test. Therefore, the optimal detection algorithm (determination of the likelihood ratio *L*) is represented by expression (4):

$$L = \left| \sum_{i=1}^{N} \sum_{j=1}^{M} e^{(j\omega_{0_i}\tau_{tr_i})} e^{(j\omega_{0_j}\tau_{rec_j})} \int_{-\infty}^{\infty} I^*_{0_j}(t - t_0) x_i(t)\,\mathrm{d}t \right| \underset{\leq}{\overset{>}{}} th, \tag{4}$$

where τ_{tr_i}, τ_{rec_j} is the time that takes into account the delay of the probing signal of the *j*-th small-sized radar at the input of the receiving device of the *i*-th small-sized radar (*i*, *j*=1, 2, ... *M*); *th* is the detection threshold, *M* is the number of small-sized radars emitting sounding signals; *N* is the number of small-sized radars that receive reflected signals.

Expression (4) is obtained taking into account the well-known Neumann-Pearson criterion [23]. The detection threshold *th* is determined taking into account the value of the conditional probability of a false alarm [23].

Taking into account expression (4), the optimal detector of a stealth unmanned aerial vehicle in a network of small-sized radars is shown in Fig. 1.

Thus, the main stages of detection of a stealth unmanned aerial vehicle by a network of small-sized radars are:

– reception of the signal reflected from a stealth unmanned aerial vehicle by all small-sized radars of the network;

– coordinated filtering (CF) of incoming signals in the *j*-th small-sized radar;

– compensation of phase shifts in each CF;

– coherent addition of output signals from each CF at the output of the receivers of each of the N small-sized receiving radars;

– formation of a complex bypass at the output of the corresponding Doppler channel in each small-sized radar of the network;

– coherent processing (adding) of signals from all elements of the network of small-sized radars;

– detection of the output signal from the adder of coherent signals. At the same time, compensation for the random initial phase of signals reflected from a stealth unmanned aerial vehicle is also performed.

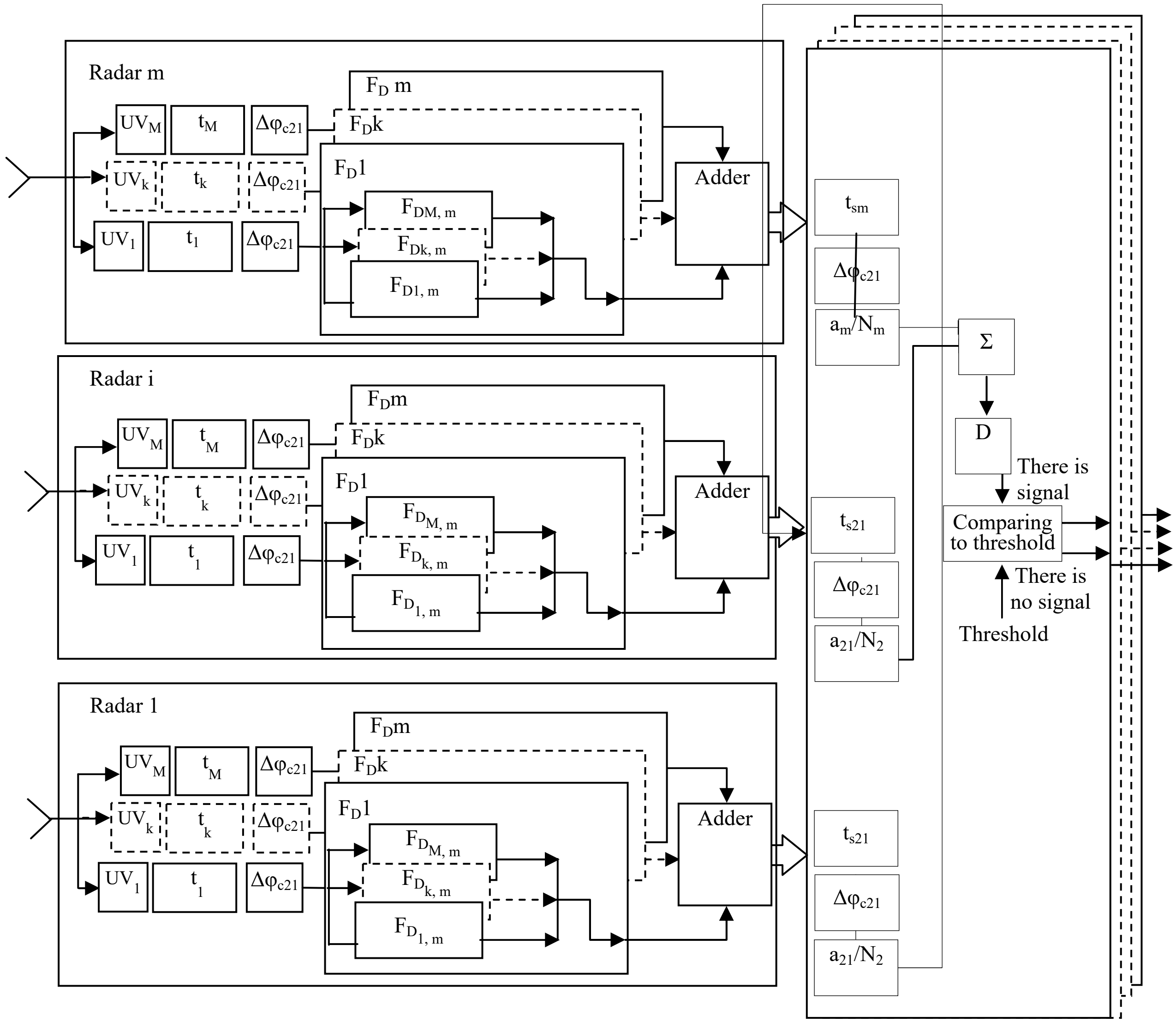

Fig. 1. Scheme of the optimal detector of a stealth unmanned aerial vehicle by a network of M small-sized radars

5. 2. Evaluation of the gain in the signal/noise ratio when adding elements to the network of small-sized radars

To determine the number of small-sized radars in the network, an assessment of the quality indicator was carried out, and we shall conduct a study of the value of such an indicator from the number of elements in the network of small-sized radars.

We shall choose the conditional probability of correct detection (for example, [26, 27]) as an indicator of the quality of the functioning of the small-sized radar network (expression (5)):

$$D = F^{\frac{1}{\left(1+\overline{q_{\Sigma}^{2}}\right)}}, \tag{5}$$

where F is the conditional probability of a false alarm; $\overline{q_{\Sigma}^{2}}$ is the average signal/noise value.

Let's calculate the average value of the signal/noise depending on the number of elements of the network of small-sized radars.

The likelihood ratio L (expression (4)) in the presence of a usable signal takes the form (expression (6)):

$$L = \sum_{i=1}^{N}\sum_{j=1}^{M} e^{\left(j\omega_{0_i}\tau_{tr_i}\right)} e^{\left(j\omega_{0_j}\tau_{rec_j}\right)} \int_{-\infty}^{\infty} I_{0_j}^{*}\left(t-t_0\right) x_i\left(t\right)\mathrm{d}t. \tag{6}$$

In the absence of a signal, the likelihood ratio L_0 takes the following form (expression (7)):

$$L_0 = \sum_{i=1}^{N}\sum_{j=1}^{M} e^{\left(j\omega_{0_i}\tau_{tr_i}\right)} e^{\left(j\omega_{0_j}\tau_{rec_j}\right)} \int_{-\infty}^{\infty} I_{0_j}^{*}\left(t-t_0\right) n_i\left(t\right)\mathrm{d}t, \tag{7}$$

where $n_i(t)$ is a function describing the noise of the ith small-sized radar.

It is known [23] that the noise amplitude is distributed according to the Gaussian law, i.e. (expression (8)):

$$\frac{1}{2}\overline{n_i\left(t_1\right) n_j^{*}\left(t_2\right)} = N_0\delta\left(t_1-t_2\right)\delta_{ij}, \tag{8}$$

where $\delta(t_1-t_2)$ is the delta function; δ_{ij} is the Kronecker symbol.

The variance of the likelihood ratio in the absence of the signal L_0 (expression (7)) is determined from expression (9):

$$\frac{1}{2}\overline{L_0^{*}L_0} = 2N_0 MN\tau_i. \tag{9}$$

The variance of the likelihood ratio in the presence of a usable signal L (expression (6)) is calculated from expression (10):

$$\frac{1}{2}\overline{L^{*}L}=2N^{2}M^{2}\overline{E_{s}}\tau_{i}. \qquad (10)$$

The average signal/noise value $\overline{q_{\Sigma}^{2}}$ is determined using expressions (9), (10), and according to expression (11):

$$\overline{q_{\Sigma}^{2}}=\frac{\frac{1}{2}\overline{L^{*}L}}{\frac{1}{2}\overline{L_{0}^{*}L_{0}}}=\frac{2N^{2}M^{2}\overline{E_{s}}\tau_{i}}{2N_{0}M\tau_{i}}=\frac{NM\overline{E_{s}}}{N_{0}}=NMq_{s}^{2}, \qquad (11)$$

where q_s^2 is the signal/noise ratio at the output of one small radar.

An assessment of the conditional probability of correct detection for the case of several elements in a network of small-sized radars was carried out. Expressions (5) and (11) were used for this purpose.

In Table 1, the conditional probabilities of correct detection are calculated for different numbers of small-sized radars in the network. The number of small radars in the network varied from one radar to eight radars.

In Fig. 2, according to the data from Table 1, detection curves are plotted for the case of several elements in a network of small-sized radars. The number of elements in the network of small-sized radars varies from one radar to eight radars.

In Fig. 2, conditional probability of correct detection depends on the signal/noise ratio. The detection curves are constructed for a conditional false alarm probability of $F=10^{-6}$.

Analysis of Fig. 2 reveals that the increase in the elements of the network of small-sized radars increases the value of the conditional probability of correct detection at a fixed value of the signal-to-noise ratio. This increase is more significant at low values of the signal/noise ratio. Also, such an increase is more significant when the number of elements in the network of small-sized radars is increased to two or three. This increase is especially significant when increasing the elements of the network of small-sized radars to four, up to five does not give such a significant gain.

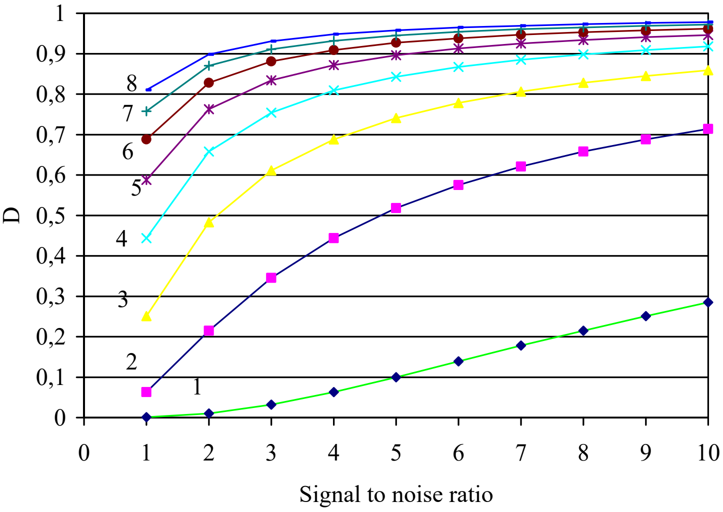

Fig. 2. Detection curves for several elements in a network of small-sized radars (the number of elements in a network of small-sized radars varies from one radar to eight radars)

An assessment of the gain K in the signal/noise ratio when adding elements to the network of small-sized radars was carried out. The gain was estimated according to the following expression (12):

$$K=20\lg\left(\frac{q_{s}^{2}}{\overline{q_{\Sigma}^{2}}}\right). \qquad (12)$$

Fig. 3 shows the dependence of the gain K on the number of elements in the network of small-sized radars M.

Table 1

Calculation of conditional probabilities of correct detection for different numbers of small radars in the network

Number of radars in the network	Parameter ID	Parameter value									
1	q_s^2	1	2	3	4	5	6	7	8	9	10
2	$\overline{q_\Sigma^2}=4q_s^2$	4	8	12	16	20	24	28	32	36	40
	D	0.063	0.215	0.345	0.444	0.518	0.575	0.621	0.658	0.688	0.714
3	$\overline{q_\Sigma^2}=9q_s^2$	9	18	27	36	45	54	63	72	81	90
	D	0.251	0.483	0.611	0.688	0.741	0.778	0.806	0.828	0.845	0.859
4	$\overline{q_\Sigma^2}=16q_s^2$	16	32	48	64	80	96	112	128	144	160
	D	0.444	0.658	0.754	0.809	0.843	0.867	0.885	0.898	0.909	0.918
5	$\overline{q_\Sigma^2}=25q_s^2$	25	50	75	100	125	150	175	200	225	250
	D	0.588	0.763	0.834	0.872	0.896	0.913	0.925	0.934	0.941	0.946
6	$\overline{q_\Sigma^2}=36q_s^2$	36	72	108	144	180	216	252	288	324	360
	D	0.688	0.828	0.881	0.909	0.927	0.938	0.947	0.953	0.958	0.962
7	$\overline{q_\Sigma^2}=49q_s^2$	49	98	147	196	245	294	343	392	441	490
	D	0.758	0.87	0.911	0.932	0.945	0.954	0.961	0.965	0.969	0.972
8	$\overline{q_\Sigma^2}=64q_s^2$	64	128	192	256	320	384	448	512	576	640
	D	0.81	0.898	0.931	0.948	0.958	0.965	0.969	0.973	0.976	0.978

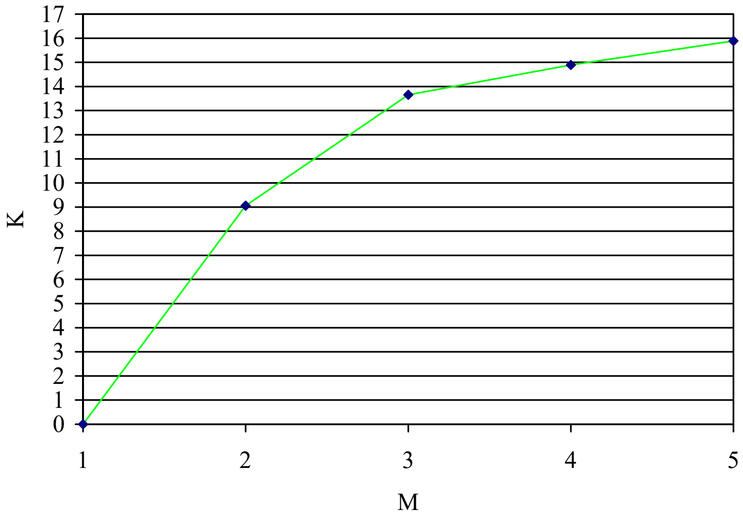

Fig. 3. Dependence of gain K on the number of elements in the network of small-sized radars *M*

Analysis of Fig. 3 reveals that combining two small-sized radars into a network provides a gain of 9 dB. Adding a third radar to the network increases the gain by 4.5 dB. Adding each subsequent one increases the gain by about 2 dB. Subsequently, there is a tendency to decrease the gain. Therefore, the greatest gain is achieved with the number of elements of the network of small-sized radars of 2–3.

Thus, the optimal number of small-sized radars in a network with coherent signal processing when detecting stealth unmanned aerial vehicles is 2–3 radars.

6. Discussion of results of the study on determining the number of small-sized radars

In the case when the network consists of *M* small-sized radars, the optimal detection algorithm according to the Neumann-Pearson criterion is represented by expression (4). Taking into account expression (4), the scheme of the optimal detector of a stealth unmanned aerial vehicle in the network of small-sized radars was constructed (Fig. 1).

The main stages of detection of a stealth unmanned aerial vehicle by a network of small-sized radars are:

– reception of the signal reflected from a stealth unmanned aerial vehicle by all small-sized radars of the network;

– coordinated filtering of incoming signals in each small-sized radar;

– compensation of phase shifts in each matched filter;

– coherent addition of output signals from each matched filter at the output of the receivers of each of the N small-sized radars performing reception;

– formation of a complex bypass at the output of the corresponding Doppler channel in each small-sized radar of the network;

– coherent processing of signals from all elements of the network of small-sized radars;

– detection of the output signal from the adder of coherent signals. At the same time, compensation for the random initial phase of signals reflected from a stealth unmanned aerial vehicle is also performed.

In order to determine the number of small-sized radars in the network, an assessment of the quality indicator was carried out and a study of the value of such an indicator from the number of elements in the network of small-sized radars was carried out. The conditional probability of correct detection (expression (5)) was chosen as the quality indicator of the functioning of the network of small-sized radars.

The average value of signal/noise was calculated depending on the number of elements in the network of small-sized radars (expression (11)). An assessment of the conditional probability of correct detection for the case of several elements in a network of small-sized radars was carried out. Expressions (5) and (11) are used for this purpose. Fig. 2 shows the constructed detection curves for the case of several elements in a network of small-sized radars. The number of elements in the network of small-sized radars varied from one radar to eight radars.

Analysis of Fig. 2 reveals that the increase in the elements of the network of small-sized radars increases the value of the conditional probability of correct detection at a fixed value of the signal-to-noise ratio. This increase is more significant at low values of the signal/noise ratio. Also, such an increase is more significant when the number of elements in the network of small-sized radars is increased to two or three. This increase is especially significant when increasing the elements of the network of small-sized radars to four, up to five does not give such a significant gain.

The gain *K* in the signal/noise ratio when adding elements to the network of small-sized radars was estimated (expression (12)). Fig. 3 shows the dependence of the gain *K* on the number of elements of the network of small-sized radars M. Analysis of Fig. 3 reveals that combining two small-sized radars into a network provides a gain of 9 dB. Adding a third radar to the network increases the gain by 4.5 dB. Adding each subsequent one increases the gain by about 2 dB. Subsequently, there is a tendency to decrease the gain. Therefore, the greatest gain is achieved with the number of elements of the network of small-sized radars of 2–3.

Thus, the optimal number of small-sized radars in a network with coherent signal processing when detecting stealth unmanned aerial vehicles is 2–3 radars.

Some limitations of our study are worth noting:

– small-sized radars must necessarily have digital signal processing;

– failure to take into account the influence of various obstacles;

– using only coherent signal processing.

The disadvantage of the detection of a stealth unmanned aerial vehicle by a network of small-sized radars is its efficiency only under the condition of coherent signal processing.

Further research should tackle the number of elements in the network of small-sized radars with incoherent processing.

7. Conclusions

1. The main stages of detection of a stealth unmanned aerial vehicle by a network of small-sized radars are:

– reception of the signal reflected from a stealth unmanned aerial vehicle by all small-sized radars of the network;

– coordinated filtering of incoming signals in each small-sized radar;

– compensation of phase shifts in each matched filter;

– coherent addition of output signals from each matched filter at the output of the receivers of each of the N small-sized radars performing reception;

– formation of a complex bypass at the output of the corresponding Doppler channel in each small-sized radar of the network;

– coherent processing of signals from all elements of the network of small-sized radars;

– detection of the output signal from the adder of coherent signals. At the same time, compensation for the random initial phase of signals reflected from a stealth unmanned aerial vehicle is also performed.

2. The gain in the signal/noise ratio when adding elements to the network of small-sized radars was evaluated. It was established that the greatest gain is achieved with the number of elements of the network of small-sized radars of 2–3. Thus, the optimal number of small-sized radars in a network with coherent signal processing when detecting stealth unmanned aerial vehicles is 2–3 radars.

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.

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