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IMPROVING A METHOD FOR NON-COHERENT PROCESSING OF SIGNALS BY A NETWORK OF TWO SMALL-SIZED RADARS FOR DETECTING A STEALTH UNMANNED AERIAL VEHICLE

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The object of this study is the process of detecting stealth unmanned aerial vehicles by a network of two small-sized radars with incoherent 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 unmanned aerial vehicles with incoherent signal processing.

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

- ***synchronous inspection of the airspace by small-sized radars;***
- ***sounding signal emission by each small-sized radar;***
- ***reception of echo signals from a stealth unmanned aerial vehicle by two small-sized radars;***
- ***coordinated filtering of incoming echo signals (separation of echo signals);***
- ***quadratic detection of signals at the outputs of matched filters;***
- ***summation of the detected signals at the outputs of the matched filters;***
- ***summation of the outputs of adders of two small-sized radars.***

The scheme of a stealth unmanned aerial vehicle detector is presented, optimal according to the Neumann-Pearson criterion, with incoherent signal processing.

The quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing was evaluated. It was found that with incoherent processing, the gain in the value of the conditional probability of correct detection is on average from 19 % to 26 %, depending on the value of the signal-to-noise ratio. The gain in the value of the conditional probability of correct detection is greater at low values of the signal-to-noise ratio. At the same time, the gain in signal-to-noise value is more significant with coherent signal processing than with non-coherent signal processing by a network of two small-sized radars

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

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1. Introduction

One of the urgent problems of high-quality air defense is the detection of stealth unmanned aerial vehicles. The relevance of the problem is confirmed by the experience of modern armed confrontations, for example, the Russian-Ukrainian war and the Israeli-Palestinian conflict [1, 2]. The most effective means of detection in the air defense system are radar stations or radars. So, for example, modern air defense systems of the leading countries of the world are equipped with small-sized radars [3, 4]. The small size of modern radars imposes certain limitations on their tactical and technical characteristics. This, in turn, leads to a decrease in the quality of detection of stealth unmanned aerial vehicles [5]. The decrease in the quality of detection of stealth unmanned aerial vehicles by small-sized radars is primarily associated with a low signal-to-noise ratio [6, 7].

One of the ways to improve the signal-to-noise ratio is to increase the energy potential by combining two small-sized radars into a network. Such an association is considered in [8]. But in [8], a restriction was adopted regarding the fulfillment of the signal coherence condition when detecting a stealth unmanned aerial vehicle.

In practice, the conditions of coherence (spatial or temporal) are not always met, or their fulfillment requires certain conditions that are not always achieved. Therefore, improving the method of incoherent signal processing by a network of two small-sized radars when detecting a stealth unmanned aerial vehicle is an urgent task.

2. Literature review and problem statement

In [9], it is proposed to increase the quality of detection of stealthy objects by radars through complicating the type and structure of probing signals. The complexity of the type and structure of sounding signals leads to the need to increase the size of radars, which is impossible in small-sized radars.

In [10], the use of a remote-sensing method for detecting a stealth unmanned aerial vehicle is proposed. This method is effective when the width of the antenna pattern is narrow. But the width of the directional pattern of a small-sized radar is not narrow, so the method [10] cannot be implemented in such a radar.

In [11], the general theoretical principles of building multi-position radar systems are considered. The results of [11] have theoretical significance and cannot be used in small-sized radars without specification.

In [12], the principles of building Multiple Input – Multiple Output (MIMO, many inputs – many outputs) radar systems are considered. The principles of construction of MIMO systems are considered and general theoretical calculations regarding the detection zones of such systems are given. The disadvantage of [12] is the impossibility of applying the given theoretical calculations for small-sized radars.

In [13], it is proposed to improve the quality of detection of stealth unmanned aerial vehicles by combining radars with mechanical rotation into a network. The disadvantage [13] is the small base of such a system and the lack of the possibility of compatible processing of the useful signal.

In [14], the energy potential of a small-sized radar is increased due to the additional energy potential of cellular signals. The disadvantage [14] is the difficulty of synchronizing the operation of the radar and cellular communication stations.

In [15], multilateration (MLAT) methods are used to improve the quality of aerial object detection. The disadvantage [15] is the impossibility of using such methods over long distances. The method works well only at distances up to several hundred meters.

In [16], the energy potential of a small-sized radar is increased due to the additional energy potential of navigation signals. The disadvantage [16] is the difficulty of synchronizing the radar and navigation satellites.

In [17], the energy potential of a small-sized radar is increased due to the additional energy potential of television signals. The disadvantage [17] is the difficulty of synchronizing the operation of the radar and digital television stations.

In [18], for the method of [17], the energy potential of a small-sized radar was evaluated taking into account the energy potential of a television signal. The disadvantage [18] is the presence of an interfering signal with a high energy potential in the additional channel.

In [19], a method of increasing the accuracy of determining the coordinates of a stealth unmanned aerial vehicle by using the Loran-C navigation system (LOng RAnge Navigation) (United States of America) is proposed. The disadvantage [19] is the impossibility of using such a method to improve the detection of an aerial object.

In [15], an increase in accuracy is achieved by using multilateration systems. The disadvantage [15] is the effective operation of such multilateration systems at a limited distance, which makes it impossible to use such systems in small-sized radars.

In [20], in contrast to [15], the use of the Wide Area Multilateration (WAM, global multilateration) system is proposed. The disadvantage [20] is the limitation of the power of WAM signals over long distances.

In [21], a method for detecting an aerial object based on the criterion of maximum likelihood is proposed. The disadvantage [21] is the complicated theoretical calculations, the use of multidimensional complex quantities, the theoretical focus of the method.

In [22], a simplification of the method [21] was proposed due to the use of the first (linear) and second (quadratic) order functions in the maximum likelihood method. The disadvantage of [22] is that it is focused more on determining the coordinates of an aerial object, the issue of detecting an aerial object is raised, but its solution is given only in general form.

In [23], the energy potential of a small-sized radar is increased due to the additional energy potential of the sound signal. The disadvantage [23] is the difficulty of synchronizing the operation of the radar and the sound signal source.

In [24], the use of an acoustic signal is proposed for the detection of an unmanned aerial object. The disadvantage of [24] is the small distance of application of the method [24].

In [25], an unmanned aerial vehicle with a multi-rotor engine is used as an aerial detection object for a small-sized radar. The disadvantage [25] is the specificity of the object of detection, and the impossibility of building a network of radars to solve the specified detection task.

In [26], the improvement of detection quality was proposed by improving the radar antenna. Changes in the construction of the radar antenna system are associated with a reduction in the radar directional pattern. The disadvantage [26] is the need to make structural changes in the construction of the radar, which is unacceptable for a small-sized radar.

In [27], methods of increasing the accuracy of determining the coordinates of a stealth unmanned aerial vehicle by improving (reducing) the width of the directional pattern of the MIMO radar system are given. The results of [27] have only theoretical value and cannot be used in the detection of stealth unmanned aerial vehicles by a network of two small-sized radars.

In [28], an overview of known methods of designing MIMO radar systems is presented. At the same time, the degree of correlation, the influence of interference, etc. is taken into account. The disadvantage [28] is the difficulty of implementing known methods in a network of two small-sized radars.

In [29], several radars are combined into a network using a genetic algorithm. The disadvantage [29] is the complexity of the practical implementation of the calculations, the possible discrepancy of the iteration process when applying the genetic algorithm.

In [30], an improved method for detecting and determining the coordinates of a stealth unmanned aerial vehicle in a network of two small-sized radars is given. Compensation of the random initial phase of the reflected signals is performed by detecting the output signal from the coherent adder. The disadvantage of [30] is that coherent signal processing is considered, which is valid only for small bases in the radar network.

Thus, the known methods of detecting stealth unmanned aerial vehicles by a network of small-sized radars involve a significant complication of information processing, complications of hardware and software components of signal processing, etc. When combining small-sized radars into a network, the main attention should be paid to methods of incoherent signal processing.

Therefore, it is necessary to conduct further research on improving the method of incoherent signal processing by a network of two small-sized radars when detecting a stealth unmanned aerial vehicle.

3. The aim and objectives of the study

The purpose of our study is to improve the quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing. This will make it possible to meet the requirements for the quality of detection of stealth unmanned aerial vehicles.

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

– to state the main stages of the method for detecting a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing;

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

4. The study materials and methods

The object of this study is the process of detecting stealth unmanned aerial vehicles by a network of two small-sized radars with incoherent 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 unmanned aerial vehicles with incoherent signal processing.

The following research methods were used during our study:

– methods of multi-position radar;

– radar location methods;

– methods of digital signal processing;

– methods of probability theory and mathematical statistics;

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

– mathematical apparatus of matrix theory;

– methods of integral and differential calculus;

– iterative methods;

– methods of system analysis;

– methods of mathematical modeling.

The following limitations and assumptions were adopted during the research:

– small-sized digital radars are considered;

– an air object with a small effective scattering surface is taken as a stealthy air object;

– examples of stealth unmanned aerial vehicles are unmanned aerial vehicles, cruise missiles, anti-radar missiles, etc. [6, 7, 31];

– each radar can receive its own reflected signal and the reflected signal from an aerial object whose probing signal is emitted by another radar;

– synchronicity of airspace inspection by small-sized radars is ensured;

– conditions for coherent processing of signals by small-sized radars are not provided;

– there are no natural and artificial obstacles;

– working wavelength of small-sized radars from 2.5 cm to 3.75 cm (X-band);

– during modeling, cruise missiles of the Kalibr type (Russian Federation) and KEPD-150/359 TAURUS (Germany-Sweden) were considered;

– velocities of stealthy air objects were assumed to be 0.6–0.95 M;

– the average effective scattering surface of stealth unmanned aerial vehicles was taken from (0.4–0.6) m^2 to (1–1.5) m^2;

– the Monte Carlo statistical test method was used in the simulation.

During simulation, the following were used:

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

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

— software: high-level programming language Python 3.11 (Netherlands).

5. Research results on improving the detection method for incoherent signal processing

5. 1. The main stages of the detection method for incoherent signal processing

By analogy with [30], the network of two small-sized radars is shown in Fig. 1. In Fig. 1, the letter B denotes the distance (base) between the radars of the network [30].

By analogy with [30], each radar of the network emits a sounding signal in the direction of a stealth unmanned aerial vehicle. At the same time, the probing signals of network radars must be mutually orthogonal. The mutual orthogonality of sounding signals can be ensured by known methods, for example, frequency methods (frequency diversity of radars) and code methods (coding of radar signals) [32].

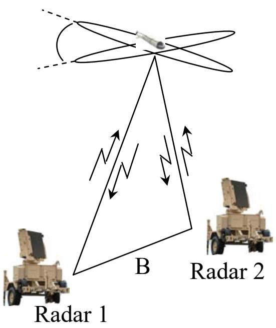

Fig. 1. A network of two small radars [30]

Mutually orthogonal probing signals are represented by expression (1) [30]:

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

where $I_{0_1}(\mathrm{t})$, $I_{0_2}(\mathrm{t})$ 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.

Mutually orthogonal sounding signals of each radar are reflected from a stealth unmanned aerial vehicle. After that, the reflected signals enter the input of the receivers of each radar. It should be taken into account that each of the radars receives both its signal reflected from the air object and the signal reflected from the air object emitted by another radar of the network. By analogy with [30], this statement is represented by expression (2):

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

where $I(t,\vec{\lambda})$ is the set of echo signals (received signals) by each radar;

$I_1(t,\vec{\lambda}_1)$, $I_2(t,\vec{\lambda}_2)$ – echo signals received, respectively, by the first and second radars.

Taking into account [30], the received echo signals of two radars (*i*=1 for the first radar; *i*=2 for the second radar) are written by expression (3):

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

where I_{s_i} is the mathematical expectation for the *i*-th signal; $\vec{\lambda}_i$ – the vector of informative parameters of the *i*-th echo signal (includes $(\varphi_{s_i}, t_{s_i}, \Omega_{s_i}, \omega_{0_i})$, where φ_{s_i} – the initial phase of the echo signal for each *i*-th radar; t_{s_i} – the delay time of the echo signal in each *i*-th radar; Ω_{s_i} – the Doppler correction to the frequency in each *i*-th radar; ω_{0_i} – the carrier frequency of the echo signal in each *i*-th radar; $I_{0_i}(t - t_{s_i})$ – the complex, normalized envelope of the *i*-th echo signal (in each one is determined by the modulation law).

In a network of two small-sized radars, signal processing and detection of a stealth unmanned aerial vehicle is determined by the degree of coherence of the receivers and the degree of mutual spatial correlation of echo signals at the inputs of the receivers of spatially dispersed radars [33].

In the following, the most difficult case is considered, when the mutual coherence of radar receivers is not ensured in the network of small-sized radars and the mutual spatial correlation of echo signals at the inputs of spatially dispersed radar receivers is not ensured.

The well-known Neumann-Pearson criterion [30, 33] was used in the synthesis of the optimal algorithm for detecting an aerial object. Taking into account the conditions of incoherent processing described above, expression (4) represents the optimal detection algorithm according to the Neumann-Pearson criterion:

$$L = \sum_{i=1}^{2}\sum_{j=1}^{2}\left|\int_{-\infty}^{\infty} I_{0i}^{*}(t - t_0)\, x_j(t)\,\mathrm{d}t\right|^2 \underset{\leq}{>} th, \tag{4}$$

where L is the likelihood ratio; $I_{0i}^{*}(t - t_0)$ – impulse characteristic of the matched filter of the signal emitted by the *i*-th radar; $x_j(t)$ is an echo signal received by the *j*-th radar receiver; *th* is the detection threshold (determined by the given conditional probability of a false alarm).

Expression (4) makes it possible to construct a scheme of a detector of a stealth unmanned aerial vehicle optimal according to the Neumann-Pearson criterion by a network of two small-sized radars with incoherent signal processing. The term "incoherent signal processing" refers to the mutual incoherence of radar receivers and the lack of mutual spatial correlation of echo signals at the inputs of spatially dispersed radar receivers. The scheme of the signal detector optimal according to the Neumann-Pearson criterion is shown in Fig. 2.

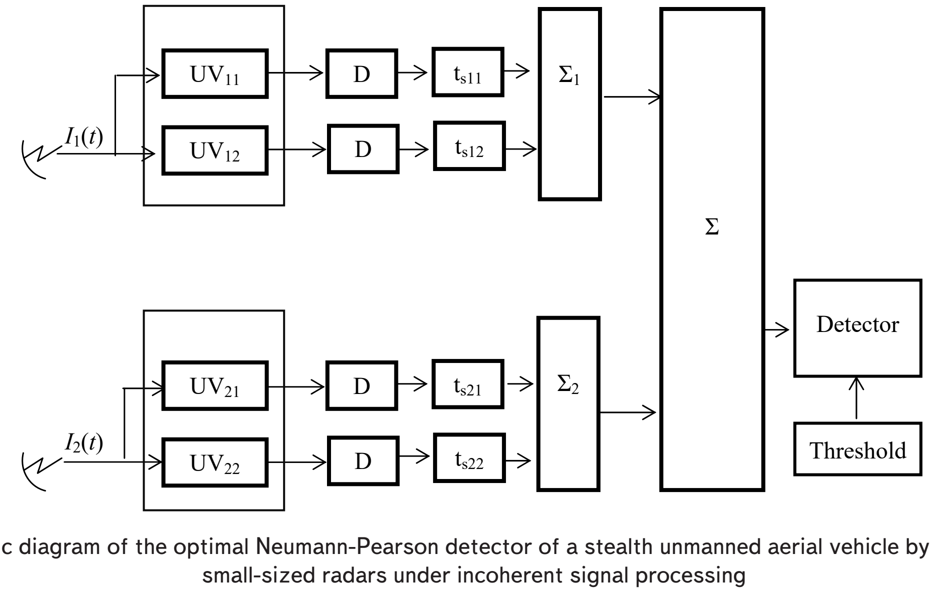

Fig. 2. Schematic diagram of the optimal Neumann-Pearson detector of a stealth unmanned aerial vehicle by a network of two small-sized radars under incoherent signal processing

The main stages of the method for detecting a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing will be determined taking into account Fig. 2 and expression (4).

Thus, the improved detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing involves:

– synchronous inspection of the airspace by small-sized radars;

– sounding signal emission by each small-sized radar;

– reception of echo signals from a stealth unmanned aerial vehicle by two small-sized radars;

– coordinated filtering of incoming echo signals (separation of echo signals);

– quadratic detection of signals at the outputs of matched filters;

– summation of the detected signals at the outputs of the matched filters;

– summation of the outputs of adders of two small-sized radars.

5. 2. Evaluation of detection quality during incoherent signal processing

The conditional probability of correct detection was chosen as an indicator of the quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing [30]. To calculate the conditional probability of correct detection, the initial statistics (likelihood ratio) were calculated in the presence and absence of an echo signal from a stealth unmanned aerial vehicle. Output statistics in the presence of an echo signal, taking into account (4), is calculated according to expression (5):

$$L_1=\sum_{i=1}^{2}\sum_{j=1}^{2}\left|\int_{-\infty}^{\infty}I_{0i}^{*}(t-t_0)\left(x_j(t)+n_j(t)\right)\mathrm{d}t\right|^2= \\ =\sum_{i=1}^{2}\sum_{j=1}^{2}\left|Z_{1ij}\right|^2, \tag{5}$$

where:

$$Z_{1ij}=\int_{-\infty}^{\infty}I_{i0}^{*}(t-t_0)\left(x_j(t)+n_j(t)\right)\mathrm{d}t$$

– correlation integral in the presence of an echo signal;

$n_j(t)$ is a function describing the noise in the j-th small radar.

The noise amplitude in the j-th small radar was assumed to be distributed according to the Gaussian (normal) law (expression (6)) [30]:

$$\frac{1}{2}\overline{n_i(t_1)n_j^{*}(t_2)}=N_0\delta(t_1-t_2)\delta_{ij}, \tag{6}$$

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

The output statistics in the absence of an echo signal, taking into account (4), are calculated according to expression (7):

$$L_0=\sum_{i=1}^{2}\sum_{j=1}^{2}\left|\int_{-\infty}^{\infty}I_{0_j}^{*}(t-t_0)n_j(t)\mathrm{d}t\right|^2=\sum_{i=1}^{2}\sum_{j=1}^{2}\left|Z_{0ij}\right|^2, \tag{7}$$

where:

$$Z_{0ij}=\int_{-\infty}^{\infty}I_{i0}^{*}(t-t_0)n_j(t)\mathrm{d}t,$$

is the correlation integral in the absence of an echo signal.

The correlation integral (7) is the sum of four squares of independent random variables that are distributed according to the Gaussian (normal) law with zero mathematical expectation and equal variances. The correlation integral can be described by the central χ^2 distribution with four degrees of freedom (expression (8)):

$$w_{L_0}(Z_0)=\frac{1}{16N_0\tau_i}Z_0*\exp\left(-\frac{Z_0}{8N_0\tau_i}\right), \tag{8}$$

where N_0 is the spectral noise density.

With the independence of amplitude fluctuations of spatially incoherent signals at the outputs of small-sized radars (absence of mutual correlation), the conditional probability of correct detection of a stealth unmanned aerial vehicle D is calculated according to expression (9):

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

The value of the detection threshold th is determined by the value of the conditional probability of a false alarm F according to expression (10):

$$F=\exp\left(-\frac{th}{1+q^2}\right)\sum_{k=1}^{2}\left(\frac{\left(\frac{th}{2}\right)^2}{k!}\right). \tag{10}$$

The relationship between the values of the signal/noise ratio when detecting a stealth unmanned aerial vehicle by an autonomous radar and a network of two small-sized radars is calculated according to expression (11) [30]:

$$\overline{q_\Sigma^2}=4q_s^2, \tag{11}$$

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

The detection curves of a stealth unmanned aerial vehicle in various cases of using small-sized radars are shown in Fig. 3.

In Fig. 3, the detection curve of a stealth unmanned aerial vehicle by one radar is represented in green. The detection curve of a stealth unmanned aerial vehicle by a network of two small-sized radars during coherent signal processing is shown in blue. The detection curve of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing is shown in yellow. When constructing the detection curves (Fig. 3), the value of the conditional probability of a false alarm was considered to be $F=10^{-6}$. The detection curve of a stealth unmanned aerial vehicle by a network of two small-sized radars during coherent signal processing is obtained from expression (12) [30]:

$$D=F^{\frac{1}{\left(1+\overline{q_\Sigma^2}\right)}}. \tag{12}$$

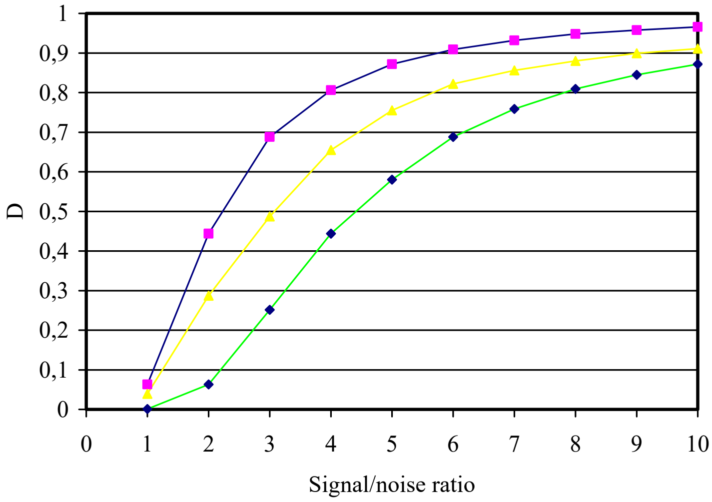

Fig. 3. Detection curves of a stealth unmanned aerial vehicle by one radar (green curve) and a network of two small-sized radars: in coherent signal processing (blue curve), in incoherent signal processing (yellow curve)

Analysis of Fig. 3 reveals that with incoherent signal processing, the gain in the value of the conditional probability of correct detection is on average from 19 % to 26 %, depending on the value of the signal/noise ratio. The gain in the value of the conditional probability of correct detection is greater at low values of the signal-to-noise ratio.

At the same time, the gain in signal-to-noise value is more significant with coherent signal processing than with non-coherent signal processing by a network of two small-sized radars.

6. Discussion of the research results regarding the improvement of the detection method for incoherent signal processing

The most complex case of incoherent signal processing is considered. Incoherent signal processing implies the absence of mutual coherence of network radar receivers and the absence of mutual spatial correlation of echo signals at the inputs of spatially dispersed radar receivers. For such a case, the likelihood ratio takes the form of (4). Expression (4) is obtained taking into account the Neumann-Pearson test. The scheme of the optimal Neumann-Pearson criterion detector of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing is shown in Fig. 2.

Improved detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing, unlike the known ones (for example, [10, 11, 30]), involves:

– synchronous inspection of the airspace by small-sized radars;

– sounding signal emission by each small-sized radar;

– reception of echo signals from a stealth unmanned aerial vehicle by two small-sized radars;

– coordinated filtering of incoming echo signals (separation of echo signals);

– quadratic detection of signals at the outputs of matched filters;

– summation of the detected signals at the outputs of the matched filters;

– summation of the outputs of adders of two small-sized radars.

The peculiarity of the method is the use of a network of two small-sized radars to detect a stealth unmanned aerial vehicle and incoherent signal processing.

The quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing was evaluated. The conditional probability of correct detection is chosen as an indicator of the quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing. We calculated output statistics (likelihood ratio) in the presence (expression (5)) and in the absence (expression (7)) of an echo signal from a stealth unmanned aerial vehicle.

We calculated conditional probability of correct detection of a stealth unmanned aerial vehicle (expression (9)). The value of the detection threshold is determined by the value of the conditional probability of a false alarm according to expression (10).

Fig. 3 shows the detection curves of a stealth unmanned aerial vehicle by one radar (green curve) and a network of two small-sized radars: with coherent signal processing (blue curve), with incoherent signal processing (yellow curve). When constructing the detection curves (Fig. 3), the value of the conditional probability of a false alarm was considered to be $F=10^{-6}$. The detection curve of a stealth unmanned aerial vehicle by a network of two small-sized radars during coherent signal processing is calculated according to expression (12).

Analysis of Fig. 3 reveals that with incoherent signal processing, the gain in the value of the conditional probability of correct detection is on average from 19 % to 26 %, depending on the value of the signal/noise ratio. The gain in the value of the conditional probability of correct detection is greater at low values of the signal-to-noise ratio. At the same time, the gain in signal-to-noise ratio is more significant with coherent signal processing than with incoherent signal processing by a network of two small-sized radars.

This study has the following limitations:

– mandatory digital signal processing in small-sized radars;

– enabling simultaneous reception of an echo signal from a stealth unmanned aerial vehicle by each small-sized radar;

– mandatory synchronization of airspace survey by a network of small-sized radars;

– the research was conducted in the absence of the influence of natural and artificial obstacles.

The disadvantage of the method for detecting a stealth unmanned aerial vehicle using a network of two small-sized radars is the difficulty of ensuring the synchronization of the airspace survey.

Further research is aimed at optimizing the geometric construction of a network of small-sized radars.

7. Conclusions

1. Improved detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing, unlike the known ones, provides for the following:

– synchronous inspection of the airspace by small-sized radars;

– sounding signal emission by each small-sized radar;

– reception of echo signals from a stealth unmanned aerial vehicle by two small-sized radars;

– coordinated filtering of incoming echo signals (separation of echo signals);

– quadratic detection of signals at the outputs of matched filters;

– summation of the detected signals at the outputs of the matched filters;

– summation of the outputs of adders of two small-sized radars.

2. We have evaluated the quality of detection of a stealth unmanned aerial vehicle by a network of two small-sized radars with incoherent signal processing. It was found that with incoherent signal processing, the gain in the value of the conditional probability of correct detection is on average from 19 % to 26 %, depending on the value of the signal/noise ratio. The gain in the value of the conditional probability of correct detection is greater at low values of the signal-to-noise ratio. At the same time, the gain in signal-to-noise value is more significant with coherent signal processing than with incoherent signal processing.

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. 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
2. Carafano, J. J. (2022). Rapid advancements in military tech. Available at: https://www.gisreportsonline.com/r/military-technology
3. Sentinel Radar. Available at: https://www.rtx.com/raytheon/what-we-do/land/sentinel-radar
4. NASAMS anti-aircraft missile system. Available at: https://en.missilery.info/missile/nasams
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. Khudov, H., Berezhnyi, A., Oleksenko, O., Maliuha, V., Balyk, I., Herda, M. et al. (2023). Increasing of the accuracy of determining the coordinates of an aerial object in the two-position network of small-sized radars. Eastern-European Journal of Enterprise Technologies, 5 (9 (125)), 6–13. https://doi.org/10.15587/1729-4061.2023.289623
9. Bezouwen, J., Brandfass, M. (2017). Technology Trends for Future Radar. Microwave Journal. Available at: http://www.microwavejournal.com/articles/29367-technology-trends-for-future-radar
10. 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
11. Chernyak, V. (2014). Signal detection with MIMO radars. Uspehi sovremennoj radiojelectroniki, 7, 35–48.
12. 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
13. 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
14. 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
15. 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
16. Willis, N. J. (2004). Bistatic Radar. Institution of Engineering and Technology. Institution of Engineering and Technology. https://doi.org/10.1049/sbra003e
17. 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
18. Ruban, I., Khudov, H., Lishchenko, V., Pukhovyi, O., Popov, S., Kolos, R., Kravets, T. 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

19. LORAN-C. Available at: https://skybrary.aero/articles/loran-c
20. Neven, W. H., Quilter, T. J., Weedon, R., Hogendoorn, R. A. (2005). Wide Area Multilateration Report on EATMP TRS 131/04 Version 1.1. Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf
21. 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
22. 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
23. 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
24. 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
25. 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
26. 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
27. Li, J., Stoica, P. (Eds.) (2008). MIMO Radar Signal Processing. John Wiley & Sons, Inc. https://doi.org/10.1002/9780470391488
28. 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
29. 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
30. 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
31. Chang, L. ZALA Lancet. Loitering munition. Available at: https://www.militarytoday.com/aircraft/lancet.htm
32. 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
33. Kishk, A., Chen, X. (Eds.) (2023). MIMO Communications - Fundamental Theory, Propagation Channels, and Antenna Systems. IntechOpen. https://doi.org/10.5772/intechopen.110927