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DEVISING A METHOD FOR DETECTING AN AERIAL OBJECT BY RADAR WITH AN ADDITIONAL CHANNEL OF PASSIVE RECEPTION

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The object of this paper is the process of detecting an aerial object by a radar with active and passive reception channels. The main hypothesis of the study assumed that the introduction of an additional channel of passive reception would increase the conditional probability of correct detection at a fixed value of the conditional probability of false alarms.

When detecting an aerial object, it was considered that the signals from aerial object represent a reflected signal after being emitted by the active radar channel elemitted own radio signals. A radar with active and passive reception channels assumes the presence of two channels. The active location channel provides reception of signals reflected from an aerial object, their processing and detection according to the Neumann-Pearson criterion. The passive location channel functions according to the principle of panoramic spectral analysis based on windowed Fourier transforms. The information combining device is intended for the compatible combining of information from active and passive channels of radar reception. At the output of the passive location channel, an output signal is formed, and the coordinates of the aerial object are measured. To ensure the functioning of the radar with active and passive reception channels, it is necessary to ensure the time synchronization of the reception channels.

The quality of detection of aerial objects by radar with active and passive signal reception channels was evaluated. The quality indicator defines the conditional probability of correct detection. The dependences of the conditional probability of correct detection are given for a radar with only an active reception channel and a radar with active and passive reception channels. It was established that the introduction of an additional channel of passive reception to the radar increases the conditional probability of correct detection by an average of (20–40) %, depending on the signal-to-noise ratio

Keywords: active radar, passive channel, conditional probability of correct detection, aerial object

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1. Introduction

The current stage of development of aerial objects is associated with a decrease in their radar visibility for active location means (active radars). By active radars, we understand those radars that "illuminate the target" and compare the parameters of the signal of their radiation and the reflected signal [1]. The direction of improving the quality of detection of inconspicuous (from the point of view of active radar) aerial objects is the construction of additional reception channels, which increases the signal-to-noise ratio and, as a consequence, indicators of the quality of detection of low observable aerial objects. As a rule, such additional reception channels use the principles of active location and certainly increase the signal-to-noise ratio.

On the other hand, when using active radars to solve air defense tasks, an essential factor is the presence of intensive measures to suppress air defense systems. Such suppression is carried out, as a rule, by setting up active obstacles and using anti-radar missiles [1]. This factor significantly reduces the quality of detection of low observable aerial objects, as well as the survivability of active radars.

One of the promising directions for increasing the survivability of radars and, at the same time, improving the quality of detection of aerial objects is the use, along with active radar, of passive channels for the detection of aerial objects. The operation of passive channels is based on the detection of aerial objects by receiving signals from on-board equipment located on aerial objects [2].

The use of only passive reception channels does not meet the requirements for the quality of radar information [2]. This is due to the relatively low value of the signal/noise ratio when receiving the own radiation of the onboard equipment of the aerial object. That is, increasing the total signal-to-noise ratio is possible only when combining active and passive channels in one radar.

The main active-passive systems are divided into the following classes:

– multi-position radar systems, in which channels with third-party radiation sources (radio and television transmission stations, satellite repeaters, etc.) are used as passive channels with the organization of coherent processing;

– multi-channel radar systems with spatial diversity of channels. At the same time, the multi-position radar system is built at the expense of scattered transmitting and receiving points, and the information received by them about the aerial object is jointly processed at one of the receiving points. Such systems are called Multiple Input Multiple Output (MIMO) radar systems;

– multi-position radar systems with cooperative reception of reflected signals. At the same time, the reception of signals in the radar is due to the radiation of both its own transmission device and other spatially dispersed transmission devices of radars that are part of such a system.

Therefore, the known active-passive systems are usually built using the principles of multi-position radar and are spread out in space. The combination of active and passive reception channels at one position for the detection of aerial objects has not been sufficiently considered in known works.

Therefore, an urgent task is the study on improving the quality of detection of an aerial object through the use of an additional channel for passive reception in an active radar.

2. Literature review and problem statement

The authors of [3] devised a method for determining the location of targets illuminated by digital satellite television signals, such as Digital Video Broadcasting (DVB): DVB-S and DVB-S2. These signals, after reradiation by the target, enter the receiving channels of passive radars with a synthesized and inverted (inverse) antenna aperture. The advantage of this method is an increase in the ability to resolve the location of surveillance objects. The peculiarity of this method is the dependence on several factors, such as the use of a stable, fully coherent transmitter and an efficient and powerful radar processor. The issue of combining DVB-S and DVB-S2 digital satellite television signal processing with active radar signals remained unresolved.

In [4], the method of signal processing in passive radars, when the target is in the illumination field of DVB-T digital television, is considered. The advantages of this method are the detection of unmanned aerial vehicles with a small value of the effective scattering surface (ESS), when the emission of signals from its own transmitting devices is not used. The disadvantage of these radars is the dependence on external sources of radiation. The issue of combining DVB-T digital television signal processing with active radar signals remained unresolved.

In [5], a new algorithm for coherent processing of global navigation satellite system (GNSS) signals in passive radars based on dynamic programming for searching and compensating inter-frame phase shift is proposed. The advantage of this algorithm is to improve the efficiency of detecting targets with a small ESS value that are in the illumination field of the GNSS system. However, the work considers the signal processing algorithm in the case when there is only one target in the radar observation area. Therefore, it is not clear what the effectiveness of this algorithm would be in the case of a multi-objective situation.

In [6], the efficiency of using a passive radar to detect aerial objects (AO) that are in the illumination field of a frequency modulation (FM) signal transmitter is considered. The method of passive interference suppression is also considered in the work. The advantage is the detection of software in a complex factory-target environment; however, the operation of this radar depends only on one third-party source of signal radiation.

In [7], a method for forming a given AO observation zone for distributed phased MIMO radars is proposed. The method involves optimization of beam weighting factors for transmission and reception channels. The time the beam stays in the observation area is also optimized.

The method involves focusing and adjusting narrow beams at all transmission and reception points in order to create an observation zone of the correct shape for timely detection and stable monitoring of software. The disadvantage of this method is the dependence of the geometric ratio of the parameters of the detection zone on the geometry of the location of the receiving and transmitting points.

In [8], recommendations were developed for the optimal placement of transmitting and receiving antennas of MIMO radars for coherent and incoherent signal processing, which are based on maximizing the determinant of the Fisher information matrix. This, in turn, is equivalent to minimizing the area of the error ellipse. These recommendations make it possible to increase the accuracy of determining the coordinates of detected targets. However, the work lacks information on the quality of radar information under the conditions of the enemy's use of active interference.

In [9], a method of focusing and controlling narrow beams of all transmitting and receiving antennas of MIMO radars at one point was developed in order to detect AO at the maximum distance in a wide observation sector. This method is based on the joint optimization of three components: the location of the focal points, the distribution of the time the beam stays in each focal point, and the order of scanning the focal points. The advantage of this method is the improvement of the quality of radar information in a complex target environment but in the work there is no information about the accuracy of determining the AO coordinates when using the proposed method.

In [10], the equation of the maximum target detection range in the MIMO system is considered. The methods of an exhaustive grid search (EGS) and a fast boundary estimation (FBE) are used. It is assumed that all transmitting and receiving beams are focused at one point.

The proposed method allows considering the dependence of the detection zone of MIMO radars on the system configuration. However, the work does not consider signal processing algorithms in this system.

In [11], combining radars into MIMO systems is proposed. At the same time, the number of radars in such a system is not determined. The disadvantage of [12] is the use of radars with a circular survey of the airspace. The question of determining the quality indicators of software detection remained unresolved.

In [13], a method of joint processing of radar and communication signals in multi-position radar systems with cooperative reception of signals was developed. The advantage of this method is to increase the reliability of information about software detection, but the work does not consider the possibility of receiving signals from aircraft on-board equipment.

In [14], for multi-position radar systems with cooperative reception of signals, a method of forming a transmission signal with minimum dispersion of the measurement error of target coordinates was devised. The proposed method makes it possible to increase the accuracy of determining AO coordinates. However, the work does not consider the detection of targets under the conditions of obstacles.

In [12], a method for protecting multi-position radar systems with cooperative reception of signals from active noise interference is considered. The method involves generating a narrow-band detection signal with high-quality autocorrelation for the receiving-transmitting radar, as well as narrow-band and wide-band decoy signals for the other two transmitting radars. The advantage of [12] is the complication of identifying the real detection signal and the deterioration of the effectiveness of jamming such multi-position systems. The disadvantage of [12] is the difficulty in ensuring the correlation characteristics of signals.

In [15], a method for increasing the accuracy of determining AO coordinates in multi-position radar systems with cooperative reception of signals due to the centralized unification of all signals used in this system was developed. The advantage of [15] is an increase in the accuracy of determining AO coordinates. The disadvantage of [15] is the provision of centralized processing of radar information.

Paper [16] proposed a method for forming multi-frequency radar signals into a multi-position radar system through the use of simultaneous radiation of partial pulses orthogonal in frequency in radars with fast electronic scanning. The advantage of [16] is an increase in the accuracy and efficiency of determining AO coordinates. The disadvantage of [16] is the difficulty of ensuring orthogonality in terms of the frequency of partial pulses.

In [17], the effect of intra-pulse modulation of multi-frequency signals in multi-position radar systems on the level of the side lobes of the autocorrelation function in the sector of airspace scanning was investigated. The advantage of [17] is the reduction of the side lobes of the autocorrelation function. The disadvantage of [17] is the technical complexity of building a radar to ensure intra-pulse modulation.

In [18], a method for increasing the conditional probability of correct detection of software by combining two small-sized radars into a network is proposed. Such association has been shown to increase the signal-to-noise ratio. The disadvantage of [18] is the mandatory provision of coherent signal processing at the central reception point.

In [19], a method of increasing the conditional probability of correct detection of software by combining two small-sized radars into a network is proposed. In contrast to [18], in [19] the case of incoherent processing is considered. The scheme of the optimal signal detector was also synthesized. The disadvantage of [19] is the complication of building a radar network and the difficulty of implementing incoherent signal processing.

In [20], the use of a Software Defined Radio (SDR) network of receivers is proposed for software detection. The signals of on-board systems, which are sources of information for the network of SDR receivers, were analyzed. The disadvantage of [20] is the complexity of the system operation at an insignificant level of signals of on-board software systems. The issue of combining the processing of signals from the SDR network of receivers and signals from active radars remained unresolved.

Our review of the literature [3–20] revealed that the advantage of combining active and passive radar methods is a compatible combination of advantages inherent in each method separately. For example, the advantages of passive systems are the absence of radiation from positions, which increases their stealth, survivability, environmental safety, and makes it possible to place them within the city infrastructure. In a certain class of passive systems, it is possible to recognize software types, and their modes of operation based on the results of analyzing the parameters of the signals emitted by their on-board equipment. The advantages of active systems are autonomy of operation, independence from external sources of radiation, constant accuracy of determining circular coordinates.

Therefore, the introduction of an additional channel of passive location to the radar is an actual area of research. Thus, it is necessary to conduct further research on improving the quality of software detection by radar with active and passive reception channels.

3. The aim and objectives of the study

The purpose of our study is to improve conditional probability of correct detection of AOs through the introduction of an additional channel of passive reception into the radar. This will make it possible to detect AOs with a low signal-to-noise ratio.

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

– to design a radar scheme with active and passive signal reception channels;

– to evaluate conditional probability of correct detection of aerial objects by a radar with active and passive signal reception channels.

4. The study materials and methods

The object of our study is the process of detecting AO by radar with active and passive reception channels. The main hypothesis of the study assumed that the introduction of an additional channel of passive reception could increase the conditional probability of correct detection at a fixed value of the conditional probability of false alarms.

The following research methods were used during the research:

– methods of system analysis;
– methods of active radar location;
– methods of passive radar;
– methods of multi-position radar;
– mathematical apparatus of matrix theory;
– methods of probability theory and mathematical statistics;
– methods of digital signal processing;
– methods of statistical theory of detection of radar signals;
– methods of mathematical modeling.

The following limitations and assumptions were adopted during the research:

– digital signal processing should be carried out in the radar;
– aircraft, unmanned aerial vehicles, cruise missiles, etc. are considered to be AOs;
– there is only one air object in the radar viewing area;
– conditions for receiving signals in active and passive reception channels are provided;
– there are no obstacles (their influence is not taken into account).

The conditional probability of correct detection was estimated by calculations. For this purpose, we used the following:

– software: Python 3.12;
– hardware: ASUSTeK COMPUTER INC model X550CC, 3rd Gen processor DRAM Controller – 0154, NVIDIA GeForce GT 720M.

5. Research results regarding the use of an additional channel of passive reception in the radar

5. 1. Design of a radar scheme with active and passive signal reception channels

AO is considered as a source of radar information. Radar information is embedded in the signals emitted by AO. It was believed that signals from AO represent:

– the signal reflected from AO after radiation by the active radar channel;
– own radio signals emitted by AO.

Signals from AO enter the active and passive radar location channels. We shall consider the radar as a set of devices that emit radio signals from objects against the background of interference.

In this case, the antenna is in the electromagnetic field $\vec{y}(t,\vec{\rho})$, which at a certain point in space is caused by a set of signals that are emitted or reflected by AO. The component of the electromagnetic field, which is determined by the set of signals coming from AO, can be represented in the form (expression (1)):

$$\vec{y}(t,\vec{\rho})=\left\{S_1(t,\vec{\lambda},\vec{\rho}),\ldots S_i(t,\vec{\lambda},\vec{\rho})\ldots S_n(t,\vec{\lambda},\vec{\rho})\right\}, \qquad (1)$$

where S_i is the i-th type of signal emitted or reflected by AO;

$\vec{\lambda}$ – vector of informative signal parameters (delay time, Doppler frequency, phase difference between lattice elements, etc.);

$\vec{\rho}$ – vector that determines the position of AO;

t – signal reception time;

i=1, 2...n – number of signal types.

The components of the electromagnetic field $\vec{y}(t,\vec{\rho})$ (expression (1)) may have different carrier frequencies, types of signal, and be caused by different sources of radiation, for example:

– own transmitter (combined with a receiving device);
– on-board AO equipment (for example, a "home-foreign" recognition device, a short-range navigation system, an on-board radar, a system for setting up active obstacles, etc.).

Each signal $S_i(t,\vec{\lambda},\vec{\rho})$, which forms an electromagnetic field $\vec{y}(t,\vec{\rho})$ (expression (1)) can be received and processed by a separate receiving channel, which is tuned to the appropriate frequency range and a certain type of signal. Therefore, to ensure the possibility of processing the entire set of signals, the receiving device must consist of a set of appropriate signal processing channels expected from AO (radiated or reflected):

– the channel of the active location;
– a passive location channel.

The structural diagram of the processing of a set of signals $S_i(t,\vec{\lambda},\vec{\rho})$ (expression (1)) for detecting and determining the coordinates of AO is shown in Fig. 1. Such a scheme (Fig. 1) will be termed a radar scheme with active and passive signal reception channels.

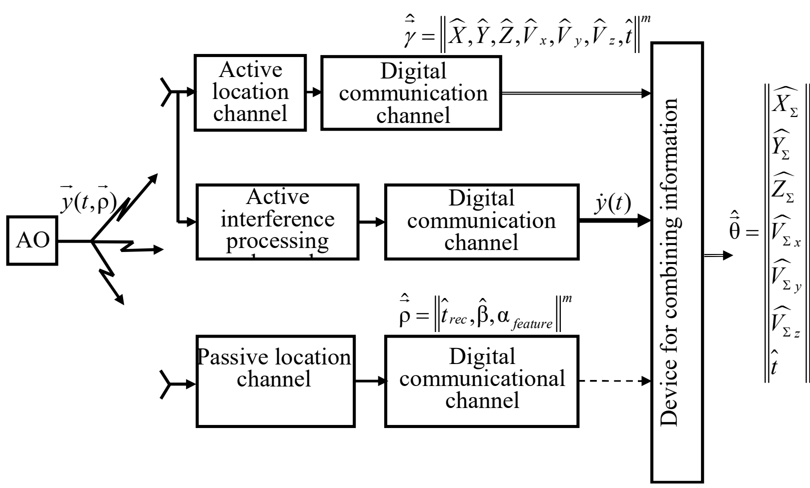

Fig. 1. Radar scheme with active and passive signal reception channels

The active location channel functions according to the algorithm (expression (2) [16]):

$$\ln Y(t,\vec{\lambda})=\frac{1}{N_0}\int_0^T\left\{Y(t,\vec{\lambda})-\hat{D}(t,\vec{\lambda})\right\}\hat{X}(t,\vec{\lambda})\mathrm{d}t-$$

$$-\frac{2}{N_0}\int_0^T\hat{X}^2(t,\vec{\lambda})\mathrm{d}t, \qquad (2)$$

where $\ln Y(t,\vec{\lambda})$ is the logarithm of the probability ratio formed at the output of the system of coordinated processing of signals that are received by the reception and processing device;

$Y(t,\vec{\lambda})$ – total input signal;

$Y(t,\vec{\lambda})-\hat{D}(t,\vec{\lambda})$ – statistics, which are formed with the help of the interference compensator;

$\widehat{D}(t,\vec{\lambda})$ – rms estimate of interfering components of the input signal, which is formed at the output of the auto compensator in the channel of the active location;

$\widehat{X}(t,\vec{\lambda})$ is the expected signal, which is implemented using the impulse response of the matched filter.

N_0 is the spectral density of white noise.

Signal detection is carried out according to the Neumann-Pearson test by comparing $\ln Y(t,\vec{\lambda})$ with the threshold q.

At the output of the channel of the active location, a vector of AO coordinate estimates is formed $\hat{\vec{\gamma}}=\left\|\widehat{X},\widehat{Y},\widehat{Z},\widehat{V}_x,\widehat{V}_y,\widehat{V}_z,\hat{t}\right\|^m$, where $(\widehat{X},\widehat{Y},\widehat{Z})$ are AO coordinate estimates, $(\widehat{V}_x,\widehat{V}_y,\widehat{V}_z)$ are AO velocity component estimates, and t is time.

The passive location channel functions according to the principle of panoramic spectral analysis based on window Fourier transforms (expression (3) [17]):

$$Z(t,\omega)=\left|\int_{-\frac{T}{2}}^{\frac{T}{2}}\dot{U}(\tau)W(\tau-t)e^{-j\omega\tau}\mathrm{d}\tau\right|, \tag{3}$$

where $Z(t,\omega)$ is the modular value of the frequency spectral harmonic ω in the received signal;

$\dot{U}(\tau)$ – complex amplitude of the received signal;

ω – circular frequency;

$W(\tau-t)$ is the window function for the Fourier transform;

T is the spectral analysis interval.

According to the results of the panoramic spectral analysis, a vector of parameters $\hat{\vec{\rho}}=\left\|\hat{t}_{rec},\hat{\beta},\hat{\alpha}_{feature}\right\|^m$, is formed at the output of the device for detecting and measuring the coordinates of the passive location channel, where $\hat{t}_{rec}$ is the time of signal reception in the passive reception channel, $\hat{\beta}$ is the evaluation of AO coordinates, $\hat{\alpha}_{feature}$ is AO feature (for example, an airplane, an unmanned aerial vehicle, a cruise missile, a balloon etc.).

The active noise processing channel is an integral part of the active radar and is designed to compensate for active noise. At the output of the active noise interference processing channel, a vector $\dot{y}(t)$, is formed consisting of signals received by the active radar at different time intervals (with a delay τ. The active noise interference processing channel functions according to the algorithm that is implemented in the information processing device according to expression (4):

$$Z(\tau)=\frac{1}{2}\left|\int_0^T y_1(t-\tau)y_2(t)\mathrm{d}t\right|, \tag{4}$$

where $y_1(t-\tau)$ and $y_2(t)$ are signals that arrive at the information combining device at different time points with a delay of τ;

$Z(\tau)$ is the cross-correlation function of signals $y_1(t-\tau)$ and $y_2(t)$.

τ is the delay between signals $y_1(t-\tau)$ and $y_2(t)$.

The information combining device is designed for the compatible combining of information from active and passive channels of radar reception.

The resulting estimate of parameters $\hat{\vec{\theta}}$ in the general case for N channels is formed by expression (5):

$$\hat{\vec{\theta}}=\vec{C}_p^{-1}\sum_{i=1}^{N}\vec{C}_i\hat{\vec{\gamma}}_i, \tag{5}$$

where $\vec{C}_p^{-1}=\sum_{i=1}^{N}\vec{C}_i$ is the resulting error matrix, i=1, 2, ... N is the channel number;

$\vec{C}_i$ – assessment accuracy matrix $\hat{\vec{\gamma}}$;

$\vec{\gamma}_i$ is a vector of parameters of the track of detected AO, which comes from all channels of the radar.

For a radar with active and passive reception channels, the resulting parameter estimate $\hat{\vec{\theta}}$ is formed by expression (6):

$$\hat{\vec{\theta}}=\vec{C}_p^{-1}\sum_{i=1}^{2}\vec{C}_i\hat{\vec{\gamma}}_i, \tag{6}$$

and represents a vector (expression (7)):

$$\hat{\vec{\theta}}=\begin{Vmatrix}\widehat{X_\Sigma}\\ \widehat{Y_\Sigma}\\ \widehat{Z_\Sigma}\\ \widehat{V_{\Sigma x}}\\ \widehat{V_{\Sigma y}}\\ \widehat{V_{\Sigma z}}\\ \hat{t}\end{Vmatrix}, \tag{7}$$

where $\left\|\widehat{X_\Sigma},\widehat{Y_\Sigma},\widehat{Z_\Sigma}\right\|^m$ are the resulting estimates of AO coordinates, $\left\|\widehat{V}_x,\widehat{V}_y,\widehat{V}_z\right\|^m$ are the resulting estimates of the components of AO velocity vector, and t is time.

To ensure the functioning of the radar with active and passive reception channels (Fig. 1), it is necessary to ensure the time synchronization of the active and passive reception channels, etc. For a combination of active and passive reception channels, it is advisable to use ring phased antenna arrays. This will allow for flexible control of the detection zone and a combination of active and passive radar operation modes. Time synchronization of active and passive channels of reception is expedient to ensure with the help of synchronization devices that are tied to the standard (single time system).

Thus, a radar with active and passive reception channels implies the presence of two channels. The active location channel provides reception of signals reflected from AO and their processing according to expression (2) and signal detection according to the Neumann-Pearson criterion. The passive location channel functions according to the principle of panoramic spectral analysis based on windowed Fourier transforms (expression (3)). At the output of the passive location channel, an output signal is formed, and AO coordinates are measured.

The information combining device is intended for the compatible combining of information from active and passive channels of radar reception. The resulting estimate of the parameters is formed by expression (6).

5. 2. Estimation of the conditional probability of correct detection of air objects by radar with active and passive signal reception channels

We shall evaluate the quality of detection of aerial objects by radar with active and passive signal reception channels. By analogy with [18, 19], the quality indicator defines the conditional probability of correct detection (expression (8)):

$$D=F^{\frac{1}{\left(1+q^2\right)}}, \tag{8}$$

where $\overline{q^2}$ is the average signal/noise value;

F is the conditional probability of a false alarm;

Expression (8) determines the conditional probability of correct detection by a radar with an active channel [18, 19]. In the presence of a radar with active and passive reception channels, the conditional probability of correct detection is determined from expression (9):

$$D = F^{\frac{1}{\left(1+\overline{q_\Sigma^2}\right)}}, \tag{9}$$

where $\overline{q_\Sigma^2}$ is the average signal/noise value in the presence of active and passive reception channels.

The average signal/noise value in the presence of active and passive reception channels is calculated according to expression (10):

$$\overline{q_\Sigma^2} = \overline{q^2} + \overline{q_{pass}^2}, \tag{10}$$

where $\overline{q_{pass}^2}$ is the signal/noise ratio in the passive receiving channel.

For comparison with known methods for increasing the conditional probability of correct detection, methods using additional radiation sources were chosen (for example, [3–6]). The value q_{add}^2 (signal/noise ratio in the passive receiving channel) is taken as a constant value, which is at least 1.5 on average [3–6].

Table 1 gives values for the conditional probability of correct detection:

– D – when using an active radar;

– D_Σ – when using a radar with active and passive reception channels.

Table 1

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

Parameter ID	Parameter value									
$\overline{q^2}$	1	2	3	4	5	6	7	8	9	10
D	0.01	0.0464	0.1	0.158	0.215	0.268	0.316	0.359	0.398	0.433
$\overline{q_{pass}^2}$	3	3	3	3	3	3	3	3	3	3
$\overline{q_{add}^2}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
D_{add}	0.072	0.13	0.187	0.242	0.293	0.338	0.379	0.416	0.449	0.477
$\overline{q_\Sigma^2}$	4	5	6	7	8	9	10	11	12	13
D_Σ	0.158	0.215	0.268	0.316	0.359	0.398	0.433	0.464	0.492	0.518

The value $\overline{q_{pass}^2}$ (signal/noise ratio in the passive receiving channel) is taken as a constant value, which is at least 3 [20]. The value of the conditional probability of a false alarm is equal to F=10^{-4}.

Fig. 2 show the constructed dependences of conditional probability of correct detection for a radar with only an active reception channel (green curve), a radar using additional radiation sources (red curve), and a radar with active and passive reception channels (black curve). When constructing Fig. 2, we used data from Table 1.

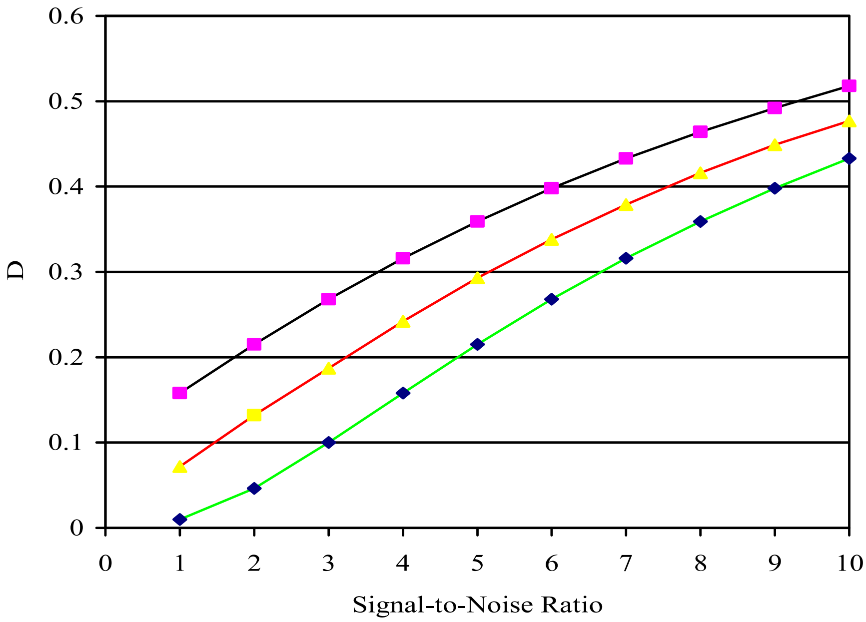

Fig. 2. Dependences of the conditional probability of correct detection for a radar with only an active reception channel (green curve), a radar using additional radiation sources (red curve), and a radar with active and passive reception channels (black curve)

Analysis of Fig. 2 reveals that the introduction of an additional channel of passive reception to the radar increases the conditional probability of correct detection by an average of (30–40) % compared to the use of a radar with an active reception channel and by (20–27) % compared to the use of a radar with additional radiation sources depending on the signal/noise ratio.

6. Discussion of research results regarding the use of an additional channel of passive reception in the radar

When detecting AO, it was considered that signals from AO represent:

– the signal reflected from AO after radiation by the active radar channel;

– own radio signals emitted by AO.

Signals from AO enter the active and passive radar location channels. A radar with active and passive reception channels assumes the presence of two channels. The scheme of the radar with active and passive signal reception channels is shown in Fig. 1. The active location channel provides reception of signals reflected from the software and their processing according to expression (2) and signal detection according to the Neumann-Pearson criterion. The passive location channel functions according to the principle of panoramic spectral analysis based on windowed Fourier transforms (expression (3)). At the output of the passive location channel, an output signal is formed, and AO coordinates are measured.

The information combining device (Fig. 1) is designed for the compatible combining of information from the active and passive channels of radar reception. The resulting estimate of the parameters is formed by expression (6).

To enable the functioning of a radar with active and passive reception channels (Fig. 1), it is necessary to ensure the time synchronization of the active and passive reception channels, etc. For a combination of active and passive reception channels, it is advisable to use ring phased antenna arrays. This will allow for flexible control of the detection zone and a combination of active and passive radar operation modes. Time synchronization of active and passive channels of reception is expedient to provide with the help of synchronization devices that are tied to the standard (single time system).

The quality of detection of aerial objects by radar with active and passive signal reception channels has been evaluated. The quality indicator defines conditional probability of correct detection (expression (8)). Expression (8) determines the conditional probability of correct detection by a radar with an active channel. In the presence of a radar with active and passive reception channels, the conditional probability of correct detection is determined by expression (9). The average signal/noise value in the presence of active and passive reception channels is calculated according to expression (10). Table 1 gives values of the conditional probability of correct detection when using an active radar and when using a radar with active and passive reception channels.

Fig. 2 shows the constructed dependences of the conditional probability of correct detection for a radar with only an active reception channel (green curve), a radar using additional radiation sources (red curve), and a radar with active and passive reception channels (black curve). When drawing Fig. 2, we used data from Table 1. Analysis of Fig. 2 reveals that the introduction of an additional channel of passive reception to the radar increases the conditional probability of correct detection by an average of (30–40) % compared to the use of a radar with an active reception channel and by (20–27) % compared to the use of a radar with additional radiation sources depending on the signal/noise ratio.

This study has the following limitations:

– there is only one AO in the radar viewing area;

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

– using only the Neumann-Pearson detection criterion.

The disadvantage of the study is that it does not take into account the case of a multi-target situation, when there are several AOs in the radar viewing area.

Under the conditions of a multi-purpose situation, with the simultaneous observation of several AOs, there is an urgent task of identifying the evaluations of AO parameters. Currently, there are known methods for eliminating false coordinate marks. This is the area of our further research.

7. Conclusions

1. A radar scheme with active and passive signal reception channels has been designed. The active location channel provides reception of signals reflected from AO and their processing and signal detection according to the Neumann-Pearson criterion. The passive location channel functions according to the principle of panoramic spectral analysis based on windowed Fourier transforms. The information combining device is intended for the compatible combining of information from active and passive channels of radar reception.

2. The quality of detection of aerial objects by radar with active and passive signal reception channels has been evaluated. It was established that the introduction of an additional channel of passive reception to the radar increases the conditional probability of correct detection by an average of (20–40) %, depending on the signal-to-noise ratio.

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, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, 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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