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IMPROVED METHOD FOR DETECTING A LOW-ALTITUDE, LOW-SPEED AERIAL OBJECT IN THE PRESENCE OF GROUND CLUTTER USING A SYNCHRONOUS MULTI-RADAR SYSTEM

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This study considers the process of detecting a low-altitude, low-speed air object in the presence of ground clutter. The principal hypothesis assumes that improving the method could make it possible to increase the signal/noise ratio.

A method has been improved for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system, which, in contrast to known ones, allows for the following:

– a synchronous survey of the airspace in azimuth and range by two radars by emitting mutually orthogonal probing signals;

– forming signals reflected from the air object at the output of the radar receivers;

– incoherent, joint signal processing in a synchronous multi-radar system from two survey radars;

– coordinated filtering of received signals;

– formation of Doppler channels;

– equalization by delay time and Doppler frequency;

– formation of an additive processing channel where incoherent summation of signals is carried out and formation of air object detection marks in the additive channel;

– formation of a multiplicative processing channel where multiplication of signals is carried out and formation of air object detection marks of the multiplicative channel;

– combination of air object detection marks of the additive and multiplicative channels and formation of final detection marks.

An experimental study was conducted on the detection of a low-altitude, low-speed air object. The use of a synchronous multiradar system made it possible to increase the signal/noise ratio by 4 times. Additional multiplicative signal processing provides an increase in the signal/noise ratio and improves the discrimination of the signal from the air object in the presence of ground clutter

Keywords: low-altitude, low-speed object; ground clutter; synchronous multiradar system; signal/noise ratio

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1. Introduction

Currently, there is a rapid evolution of low-visibility, low-speed air objects. Due to their small size, such objects

are used for monitoring, solving logistical tasks, as well as surveillance tasks, including in military affairs [1, 2].

It is noted in [3] that such low-visibility, low-speed air objects are atypical for detection by modern radars. This is pri-

marily due to their small geometric dimensions and low radar visibility. In addition, signals reflected from such air objects are usually masked by reflections from the ground clutter. This fact leads to a decrease in the quality of detection of low-visibility, low-speed air objects [4]. In addition, selection by Doppler frequency of such air objects is also complicated. This is due to partial or complete overlapping of the characteristics of the signals with the spectrum of reflections from the ground clutter. Under such conditions, the quality of known methods for detecting low-altitude, low-speed aerial objects in the presence of ground clutter is significantly reduced.

Therefore, it is a relevant task to solve the task of improving a method for detecting low-altitude, low-speed aerial objects in the presence of ground clutter.

2. Literature review and problem statement

In [5], a method was proposed for selecting moving targets based on the use of features in the rotation of propellers of an unmanned aerial vehicle (UAV). The method makes it possible to detect such UAV, but only at very short ranges. This requires an increase in the effective scattering surface of the unmanned aerial vehicle. This approach is considered in [6]. In it, an artificial increase in the effective scattering surface of an air object is proposed. This led to an improvement in the quality of detecting such air objects in the presence of ground clutter. The disadvantage is the artificial increase in the effective scattering surface, which is complicated under actual conditions.

A method for preliminary suppression of reflections from the ground clutter is proposed in [7]. It improves the quality of detecting signals from inconspicuous air objects. The disadvantage is the need to pre-set the parameters for suppressing reflections from the ground clutter.

In [8], a deep learning method is proposed for suppressing reflections from the ground clutter. The method involves automatic learning and adaptation to the ground clutter model. The disadvantage is the availability of a training sample and significant computational resources.

In [9], an improved method for selecting moving targets using a sparse component signal is proposed. This approach improves the quality of selection in the presence of ground clutter. The disadvantage is that it does not take into account the case of complete overlap of the spectra of an air object and reflections from the ground clutter.

A multi-position radar network was proposed in [10] to improve the quality of air object detection. The disadvantage is the impossibility of detecting a low-visibility, low-speed air object under conditions of reflections from the ground clutter. To overcome this disadvantage, a change in the frequency of the radar transmitter was proposed.

A change in the frequency of the radar transmitter was proposed in [11] to improve the quality of air object detection. The disadvantage is the low accuracy in determining the coordinates of the air object.

In [12], a multi-position network of two-coordinate radars was suggested to improve the quality of signal detection from low-visibility air objects. The disadvantage is the impossibility of ensuring synchronous airspace survey.

The use of a Multiple Input – Multiple Output (MIMO) radar system was proposed in [13] to improve the quality of signal detection from low-visibility air objects. The disadvantages of are signal processing under incoherent conditions and

high system cost. Coherent signal processing is considered in [14]. In it, a method for detecting a group of unmanned aerial vehicles is suggested. The disadvantages are the low signal-to-noise ratio, which, in turn, affects the accuracy of determining the coordinates of air objects.

In [15], an additional source of information is used to improve the quality of detecting signals from low-visibility air objects. The disadvantages are the complexity of synchronizing the operation of radars and the additional source of information.

A method for restoring the spectrum of signals reflected from the ground clutter is proposed in [16]. In this case, only the main components of such a spectrum are taken into account. This significantly reduces the need to use training samples. The disadvantage is the loss of part of the information regarding the spectrum of the signal reflected from the ground clutter.

In [17], a method for detecting an unmanned aerial vehicle based on the analysis of Doppler features is offered. Methods for processing signals in time and frequency are analyzed. The disadvantage is the lack of practical use of the proposed methods.

Thus, our review of known methods for detecting low-altitude, low-speed aerial objects in the presence of ground clutter indicates the following shortcomings:

- low signal-to-noise ratio;
- difficulty in ensuring synchronous operation of radars;
- failure to take into account the features of signals from the ground clutter;
- high computational complexity;
- difficulty in practical implementation.

The above indicates the feasibility of a study aimed at improving a method for detecting a low-altitude, low-speed aerial object in the presence of ground clutter.

3. The aim and objectives of the study

The purpose of our study is to increase the signal-to-noise ratio when detecting a low-altitude, low-speed air object in the presence of ground clutter by combining radars into a synchronous multi-radar system. The use of a synchronous multi-radar system could make it possible to increase the signal-to-noise ratio when detecting a low-altitude, low-speed air object in the presence of ground clutter.

To achieve the goal, the following tasks were set:

- to define key stages in a method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system;
- to conduct an experimental study on the detection of a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system.

4. The study materials and methods

The object of our study is the process of detecting a low-altitude, low-speed air object in the presence of ground clutter.

The principal hypothesis assumes that improving a method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system could make it possible to increase the signal/noise ratio.

The following assumptions were adopted during the study:

- a multi-radar system is used;
- surveillance radars are taken as elements of the system;
- the radio receiver of each radar is digital;

- airspace is surveyed in azimuth and range;
- reflections from the ground clutter were considered as interfering;
- the air object was considered to be low-altitude and low-speed;
- joint processing of signals from elements of the multi-radar system is incoherent.

When conducting the study, the following simplifications were accepted:

- the multi-radar system is synchronous (synchronous airspace survey is provided);
- when conducting the experimental study, the number of elements of the multi-radar system was taken to be two radars;
- the sounding signals emitted by the radars of the multi-radar network are mutually orthogonal;
- the orthogonality of the sounding signals emitted by the radars of the multi-radar network was ensured by shifting the carrier frequency of the signal of the first radar relative to the second radar;
- other interfering artifacts were not considered.

Our experimental study employed the following:

- hardware: DELL Intel(R) Core(TM) i7-8650U CPU @ 1.90GHz (2.11 GHz) laptop (USA);
- software: high-level programming language and interactive environment for programming, numerical calculations, and visualization of results MATLAB R2017b (United States of America).

The following general methods were used in the study:

- system analysis;
- radar location;
- multi-position radar;
- digital signal processing;
- statistical theory of detection and measurement of radar signal parameters;
- spectral analysis;
- probability theory and mathematical statistics;
- mathematical apparatus of matrix theory;
- mathematical modeling;
- empirical research;
- comparative research.

This study's methods were selected taking into account the research objectives set above.

When defining key stages in a method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system, the following theoretical methods were used:

- system analysis;
- radar location;
- multi-position radar;
- digital signal processing;
- statistical theory of detection and measurement of radar signal parameters;
- spectral analysis;
- probability theory and mathematical statistics;
- mathematical apparatus of matrix theory.

When conducting an experimental study on the detection of a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system, the following theoretical and practical research methods were used:

- radar location;
- multi-position radar;
- digital signal processing;
- statistical theory of detection and measurement of radar signal parameters;

- mathematical modeling;
- empirical research;
- comparative research.

The system analysis method was used for the following:

- construction of a configuration of a synchronous multi-radar system from two surveillance radars;
- study of connections between elements of a multi-radar system;
- defining key stages in the detection method.

Radar methods were used for the following:

- analysis of the process of signal formation at the output of radar receivers (Radar 1 and Radar 2);
- determination of the features of reflected signals from an air object and from the ground clutter;
- carrying out incoherent joint signal processing using a synchronous multi-radar system from two surveillance radars;
- formation of an additive processing channel;
- formation of a multiplicative processing channel.

Multi-position radar methods were used for the following:

- determination of the features of joint signal processing using a synchronous multi-radar system from two surveillance radars;
- synchronization of elements of a synchronous multi-radar system from two surveillance radars;
- combining the air object detection marks of the additive and multiplicative channels and forming the final detection marks.

Digital signal processing methods were used for the following:

- preprocessing of signals in each of the elements of the synchronous multi-radar system of two surveillance radars;
- separation of the useful signal from the air object against the background of the ground clutter;
- formation of spatial-temporal signals from the air object and from the ground clutter;
- coordinated filtering of received signals;
- formation of Doppler channels;
- equalization by delay time and Doppler frequency;
- formation of an adaptive threshold in accordance with the specified indicators of signal detection quality (conditional probability of correct detection and conditional probability of false alarm).

Methods of the statistical theory of detection and measurement of radar signal parameters were used for the following:

- construction of a structural diagram of a joint incoherent signal processing using a synchronous multi-radar system of two surveillance radars;
- construction of a structural diagram of the joint incoherent signal processing in the joint incoherent processing device of a synchronous multi-radar system consisting of two surveillance radars.

The methods of spectral analysis were used for the following:

- construction of Doppler characteristics of signals from an air object and from the ground clutter;
- frequency selection of signals from an air object and from the ground clutter.

The methods of probability theory and mathematical statistics were used for the following:

- representation of noise, fluctuations of signals reflected from an air object and from the ground clutter;
- evaluation of statistical characteristics of signals reflected from an air object and from the ground clutter;
- conducting an experimental study on the detection of a low-altitude, low-speed air object;

- confirmation of the reliability of the results of an experimental study on the detection of a low-altitude, low-speed air object.
- The mathematical apparatus of matrix theory was used for the following:
 - mathematical formalization of multi-channel signal processing using a synchronous multi-radar system of two surveillance radars;
 - spatial-temporal signal processing using a synchronous multi-radar system of two surveillance radars.
- Mathematical modeling methods were used:
 - to reproduce the processes of radar signal propagation;
 - to form signals reflected from an air object and from the ground clutter;
 - to conduct an experimental study on the detection of a low-altitude, low-speed air object.
- Empirical research methods were applied:
 - to conduct an experimental study on the detection of a low-altitude, low-speed air object;
 - to obtain practical results on the detection of a low-altitude, low-speed air object;
 - to confirm the reliability of results from the experimental study on the detection of a low-altitude, low-speed air object.
- The comparative research method was used to compare the improved and known detection methods by the signal-to-noise ratio.

5. Results of investigating a method for detecting a low-altitude, low-speed aerial object

5.1. Key stages in the method for detecting a low-altitude, low-speed aerial object

The configuration of a synchronous multi-radar system consisting of two surveillance radars is shown in Fig. 1.

Key stages in the method for detecting a low-altitude, low-speed aerial object are as follows:

1. Radars (Radar 1, Radar 2) conduct a synchronous survey of the airspace in azimuth and range. Radar 1 and Radar 2 emit mutually orthogonal probing signals. Orthogonality is ensured by shifting the carrier frequency of the Radar 1 signal relative to Radar 2. It was assumed that a low-altitude, low-speed aerial object is detected in the presence of ground clutter. The aerial object is detected based on the results of joint incoherent signal processing in a joint incoherent processing device (JIPD).
2. At the output of the radar receivers (Radar 1 and Radar 2), signals are formed in accordance with expressions (1), (2):

$$y_1(t) = s_1(t - t_{d1}) + s_{12}(t - t_{d12}) + g_1(t) + g_{12}(t) + n_1(t), \tag{1}$$

$$y_2(t) = s_2(t - t_{d2}) + s_{21}(t - t_{d21}) + g_2(t) + g_{21}(t) + n_2(t), \tag{2}$$

where $y_1(t)$, $y_2(t)$ are the signals at the input of the Radar 1 and Radar 2 receivers, respectively;

$s_1(t_{d1})$ is the echo signal received in Radar 1 and caused by the reflection of the Radar 1 sounding signal from an air object;

$s_2(t_{d2})$ is the echo signal received in Radar 2 and caused by the reflection of the Radar 2 sounding signal from an air object;

$s_{12}(t - t_{d12})$ is the echo signal received in Radar 1 and caused by the reflection of the Radar 1 sounding signal from an air object;

- $s_{21}(t - t_{d21})$ is the echo signal received in Radar 2 and caused by the reflection of the Radar 2 sounding signal from an air object;
- $g_1(t)$ – echo signal received in Radar 1 and caused by reflection from the ground clutter of the Radar 1 sounding signal;
- $g_2(t)$ – echo signal received in Radar 2 and caused by reflection from the ground clutter of the Radar 2 sounding signal;
- $g_{12}(t)$ – echo signal received in Radar 1 and caused by reflection from the ground clutter of the probing signal Radar 2;
- $g_{21}(t)$ – echo signal received in Radar 2 and caused by reflection from the ground clutter of the probing signal Radar 1;
- $n_1(t)$, $n_2(t)$ – intrinsic noises of the receiving devices Radar 1 and Radar 2, respectively;
- t_{d1} – echo delay time in Radar 1, which is caused by distance R_1 ;
- t_{d2} – echo delay time in Radar 2, which is caused by distance R_2 ;
- t_{d21} – echo delay time in Radar 2, which is caused by distance $(R_1 + R_2)$;
- t_{d12} – echo delay time in Radar 1, which is caused by distance $(R_2 + R_1)$;
- θ – angle between directions on Radar 1 and Radar 2 from the side of the air object.

3. Incoherent joint signal processing is performed using a synchronous multi-radar system of two surveillance radars. The block diagram of the joint incoherent signal processing using a synchronous multi-radar system of two surveillance radars is shown in Fig. 2.

Echo signals are received in Radar 1 and Radar 2 using an antenna system (AS) and a digital radio receiver (DRR) [18]. In each sounding period, the received signals are filtered using digital filters. The digital filters are matched filters (MF) for the sounding signal from Radar 1 (MF 1) and Radar 2 (MF 2). Devices MF 1 and MF 2 on each sounding perform matched digital filtering of the signals emitted by Radar 1 and Radar 2, respectively (expressions (3) to (6)).

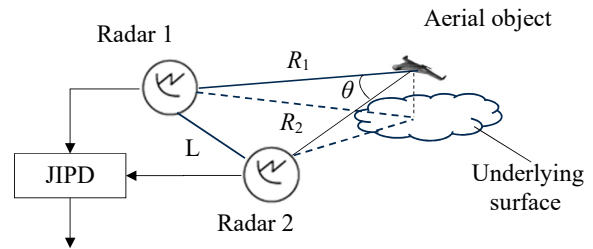


Fig. 1. Configuration of a synchronous multi-radar system with two surveillance radars

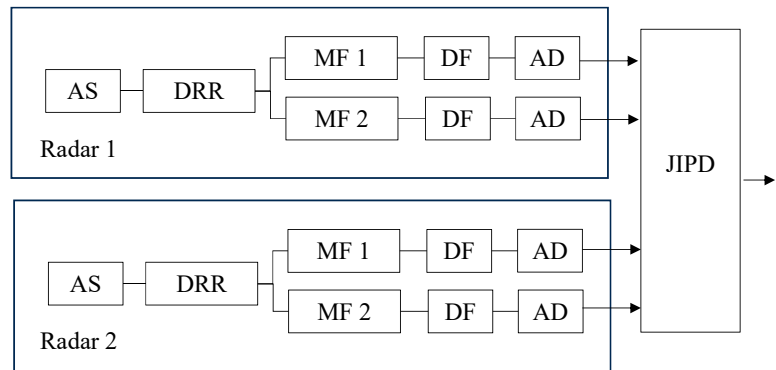


Fig. 2. Block diagram of joint incoherent signal processing using a synchronous multi-radar system with two surveillance radars

Devices MF 1 and MF 2 on each sounding perform matched digital filtering of the signals emitted by Radar 1 and Radar 2, respectively, according to the following expressions:

$$z_{11}(t_i) = \int_{-\infty}^{\infty} (y_1(t-t_i)x_1(t))dt, \tag{3}$$

$$z_{12}(t_i) = \int_{-\infty}^{\infty} (y_1(t-t_i)x_2(t))dt, \tag{4}$$

$$z_{21}(t_i) = \int_{-\infty}^{\infty} (y_2(t-t_i)x_1(t))dt, \tag{5}$$

$$z_{22}(t_i) = \int_{-\infty}^{\infty} (y_2(t-t_i)x_2(t))dt, \tag{6}$$

where $z_{11}(t_i)$ – signal at the output of MF 1 Radar 1; $z_{12}(t_i)$ – signal at the output of MF 2 Radar 1; $z_{21}(t_i)$ – signal at the output of MF 1 Radar 2; $z_{22}(t_i)$ – signal at the output of MF 2 Radar 2; $x_1(t)$ – impulse response of the filter corresponding to the signal emitted by Radar 1; $x_2(t)$ – impulse response of the filter corresponding to the signal emitted by Radar 2; t_i – delay time for which signals are formed; $i = (0...m)$ – signal delay interval.

After the output of the matched filters, a packet of signals received during N sounding periods is fed to the Doppler filters (DF). At the output of DF after the amplitude detector (AD), signals are formed for each delay time (expressions (7) to (10)):

$$g_{11}(t_i, f_d) = \left| FFT \left(\left[z_{11}(t_i, 1), \dots, z_{11}(t_i, k), \dots, z_{11}(t_i, N) \right] \right) \right|, \tag{7}$$

$$g_{12}(t_i, f_d) = \left| FFT \left(\left[z_{12}(t_i, 1), \dots, z_{12}(t_i, k), \dots, z_{12}(t_i, N) \right] \right) \right|, \tag{8}$$

$$g_{21}(t_i, f_d) = \left| FFT \left(\left[z_{21}(t_i, 1), \dots, z_{21}(t_i, k), \dots, z_{21}(t_i, N) \right] \right) \right|, \tag{9}$$

$$g_{22}(t_i, f_d) = \left| FFT \left(\left[z_{22}(t_i, 1), \dots, z_{22}(t_i, k), \dots, z_{22}(t_i, N) \right] \right) \right|, \tag{10}$$

where $FFT()$ is the fast Fourier transform (FFT) function; $|\cdot|$ is the signal modulus calculation function; f_d is the Doppler frequency; t_i is the delay time for which FFT is performed; $k = (1...N)$ is the probe number, N is the number of probes per irradiation time that form a packet.

In this way, Doppler channels are formed.

Signals from DF outputs after amplitude detection (AD) enter JIPD. After equalization by delay time and Doppler frequency, joint incoherent signal processing and detection of an air object are performed. The structural diagram of JIPD is shown in Fig. 3.

In Fig. 3, signals from AD outputs of Radar 1 and Radar 2 are fed to the additive processing channel (Σ) where their incoherent summation is carried out. At the input of the device Σ of the additive processing channel (Fig. 3), a final signal is formed according to expression (11)

$$a(t_i, f_d) = \sum_{m=1}^4 (g_m(t_i, f_d)), \tag{11}$$

where $g_m(t_i, f_d)$ is the signal formed at the outputs of AD according to expressions (7) to (10).

From the output of the additive processing channel, the final signal is fed to the additive channel detection device (DD_{Σ}), where:

- an adaptive threshold is formed in accordance with the specified indicators of signal detection quality (conditional probability of correct detection and conditional probability of false alarm);
- signals that exceed the detection threshold are detected;
- air object detection marks are formed in the additive channel.

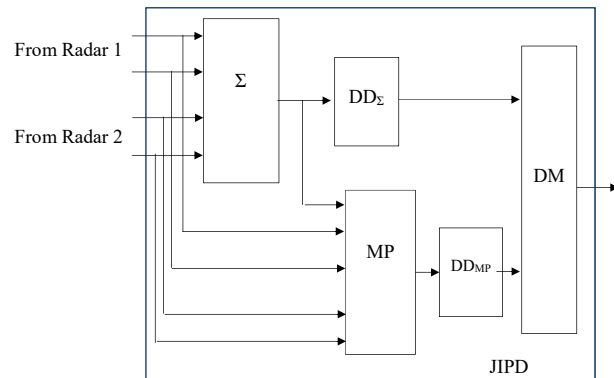


Fig. 3. Block diagram of the joint incoherent signal processing in the joint incoherent processing device of a synchronous multi-radar system of two surveillance radars

Signals from the output of the additive processing channel (Σ) and signals from AD outputs of Radar 1 and Radar 2 are fed to the multiplicative processing channel (MP) where they are multiplied. At the input of device MP of the multiplicative processing channel (Fig. 3), a final signal is formed according to expression (12)

$$p(t_i, f_d) = a(t_i, f_d) \sum_{m=1}^4 (g_m(t_i, f_d)), \tag{12}$$

where $a(t_i, f_d)$ is the signal formed at the output of the additive processing channel according to expression (11).

From the output of the multiplicative processing channel, the final signal is fed to the multiplicative channel detection device (DD_{MP}) where:

- an adaptive threshold is formed in accordance with the specified indicators of signal detection quality (conditional probability of correct detection and conditional probability of false alarm);
- signals exceeding the detection threshold are detected;
- air object detection marks of the multiplicative channel are formed.

From the DD_{Σ} and DD_{MP} outputs, air object detection marks are fed to the decision-making device (DM). In the DM device, the air object detection marks of the additive and multiplicative channels are combined, and the final detection marks are formed.

Thus, a method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system has been improved, which, in contrast to known ones, provides for the following:

- a synchronous survey of the airspace in azimuth and range by two radars by emitting mutually orthogonal probing signals;
- forming at the output of the radar receivers of signals reflected from the air object;
- incoherent combined processing of signals using a synchronous multi-radar system from two survey radars;
- coordinated filtering of received signals;

- formation of Doppler channels;
- equalization by delay time and Doppler frequency;
- formation of an additive processing channel, where incoherent summation of signals and formation of air object detection marks in the additive channel are carried out;
- formation of a multiplicative processing channel, where signals are multiplied and air object detection marks of the multiplicative channel are formed;
- combination of air object detection marks of the additive and multiplicative channels and formation of final detection marks.

5. 2. Experimental study on the detection of a low-altitude, low-speed aerial object

To conduct an experimental study on the detection of a low-altitude, low-speed aerial object, the Monte Carlo statistical test method was used.

When conducting an experimental study, the following assumptions and limitations were accepted:

- surveillance radars were adopted as elements of the multiradar system;
- reflections from the ground clutter were considered interfering;
- the aerial object was considered low-altitude and low-speed;
- joint processing of signals from the elements of the multiradar system is incoherent;
- synchronous airspace inspection is ensured;
- the number of elements of the multiradar system is equal to two radars;
- the sounding signals emitted by the radars of the multiradar network are mutually orthogonal;
- other interfering artifacts were not considered;
- $R_1 = R_2$, which determines the equality of the delay time for echo signals received at the RADAR 1 and Radar 2 positions ($t_{d1} = t_{d2} = t_{d21} = t_{d12}$);
- the speed of the air object is so small that the echo signal from the air object and the echo signals from the ground clutter are in the same Doppler filter.

The echo signal packets from a low-altitude, low-speed air object and from the ground clutter are shown in Fig. 4, 5, respectively. The packets (Fig. 4, 5) enter the MF input (Fig. 2).

At the MF output, echo signal packets from a low-altitude, low-speed aerial object and from the ground clutter are shown in Fig. 6, 7, respectively.

Echo signals from a low-altitude, low-speed aerial object and from the ground clutter at the exit (DF+AD) are shown in Fig. 8, 9, respectively.

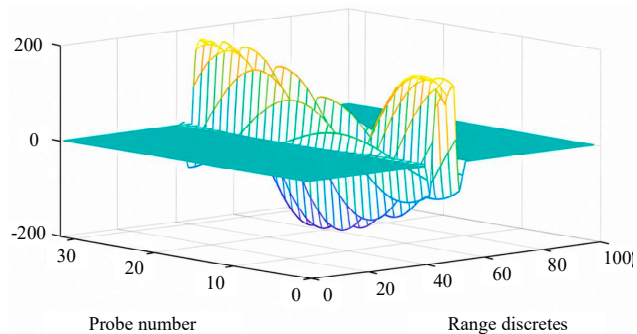


Fig. 4. A packet of echo signals from a low-altitude, low-speed airborne object at the input of a matched filter

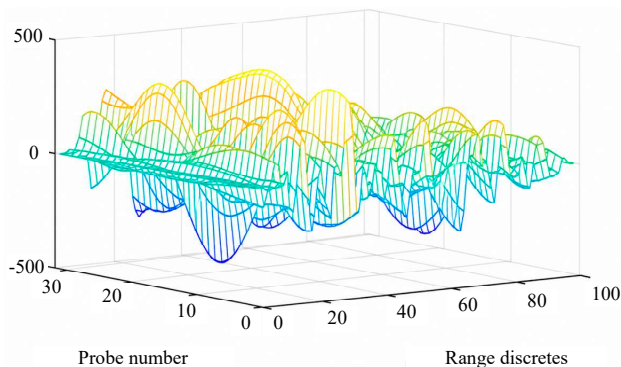


Fig. 5. A packet of echo signals from the ground clutter at the input of a matched filter

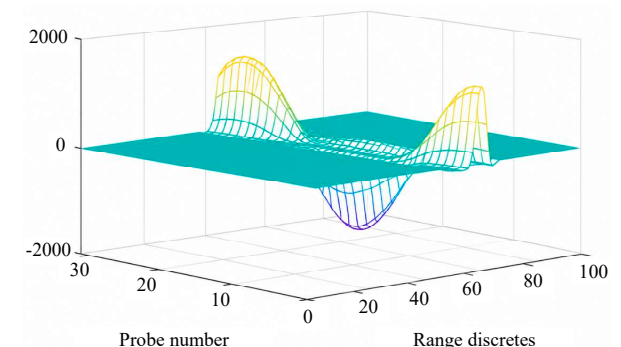


Fig. 6. Echo signals from a low-altitude, low-speed airborne object at the output of a matched filter

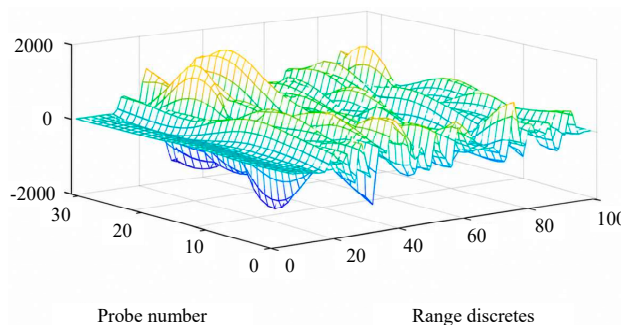


Fig. 7. Echo signals from the ground clutter at the output of the matched filter

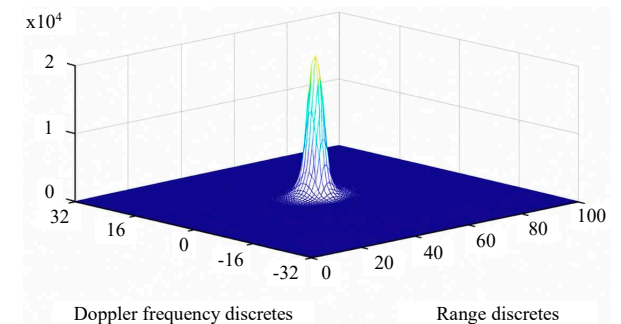


Fig. 8. Echo signals from a low-altitude, low-speed airborne object at the exit (Doppler filter + amplitude detector)

Analysis of Fig. 8, 9 reveals that the echo signals from a low-altitude, low-speed aerial object and from the ground clutter are in the same discrete Doppler frequency. This fact is illustrated in Fig. 10.

The echo signals at the output (DF+AD) of RADAR 1 from RADAR 1 and from RADAR 2 are shown in Fig. 11, 12, respectively.

The echo signals at the output (DF+AD) of RADAR 2 from RADAR 1 and from RADAR 2 are shown in Fig. 13, 14, respectively.

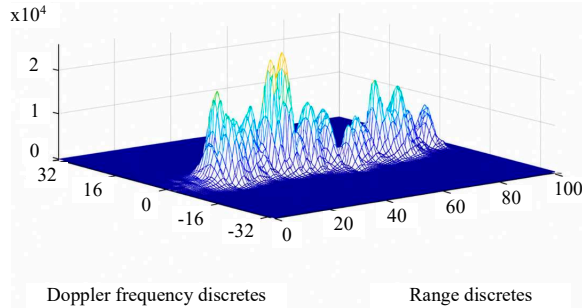


Fig. 9. Echo signals from the ground clutter at the output (Doppler filter + amplitude detector)

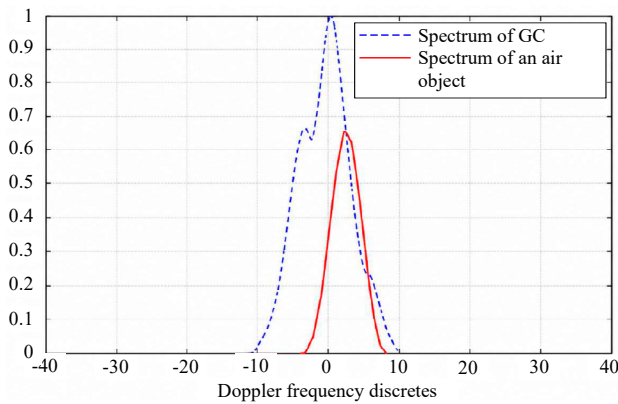


Fig. 10. Location of Doppler spectra of echo signals from the ground clutter and from a low-altitude, low-speed airborne object at the exit (Doppler filter + amplitude detector)

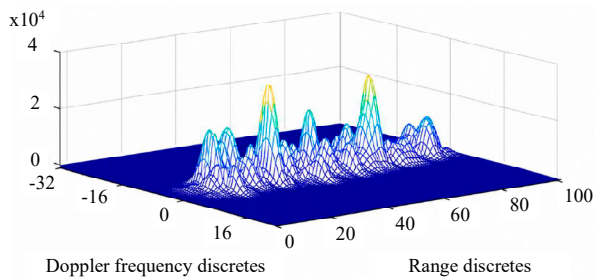


Fig. 11. Echo signals at the output (Doppler filter + amplitude detector) RADAR 1 from RADAR 1

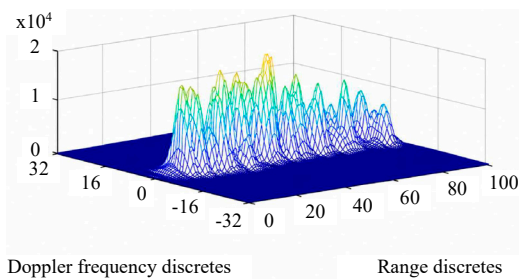


Fig. 12. Echo signals at the output (Doppler filter + amplitude detector) RADAR 1 from RADAR 2

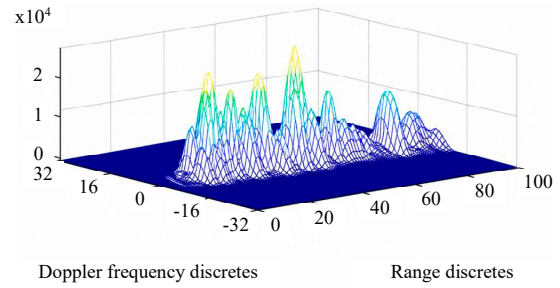


Fig. 13. Echo signals at the output (Doppler filter + amplitude detector) RADAR 2 from RADAR 2

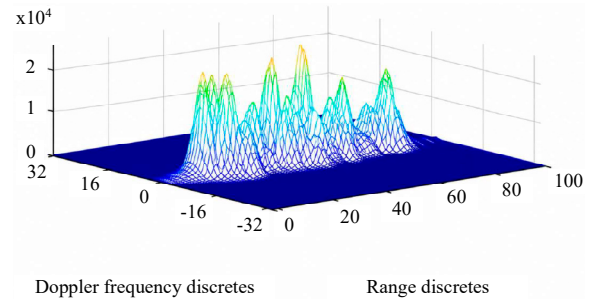


Fig. 14. Echo signals at the output (Doppler filter + amplitude detector) RADAR 2 from RADAR 2

The signals at different stages of processing are shown in Fig. 15–17. Fig. 15 depicts signals at the AD output of Radar 1 and Radar 2. Fig. 16 illustrates the final signal at the output of the additive processing channel (Σ). Fig. 17 shows the final signal at the output of the multiplicative processing channel (MP)

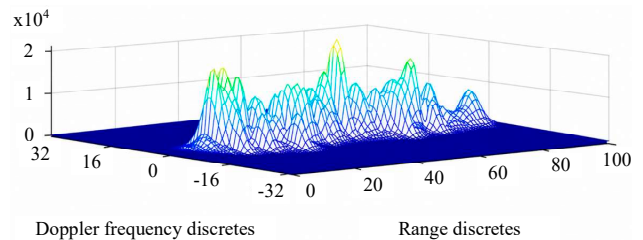


Fig. 15. Signals at the output of the amplitude detector Radar 1 and Radar 2

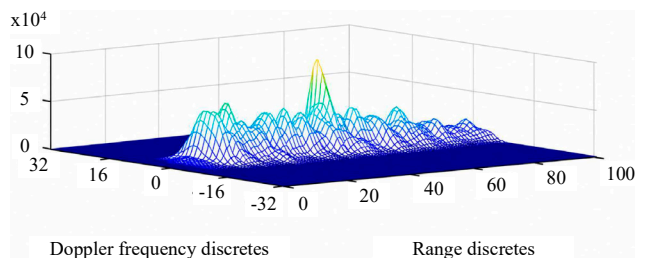


Fig. 16. The final signal at the output of the additive processing channel (Σ)

Analysis of Fig. 17 reveals a clear separation of the signal from a low-altitude, low-speed aerial object in the presence of ground clutter.

To assess the gain in the signal/noise ratio of the improved method, Fig. 18 shows the signals: input (blue), at the output of the additive processing channel (black) and at the output of the multiplicative processing channel (red).

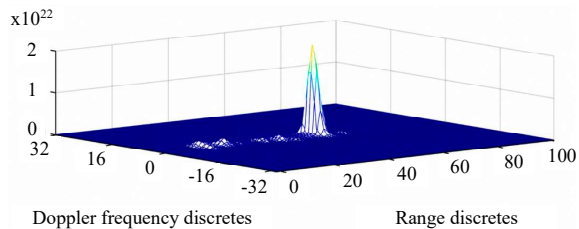


Fig. 17. The final signal at the output of the multiplicative processing channel (MP)

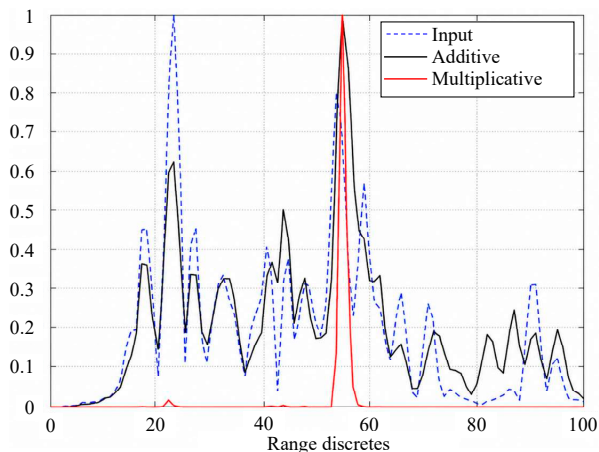


Fig. 18. Signals: input (blue), output of the additive processing channel (black), and output of the multiplicative processing channel (red)

From the analysis of Fig. 18, it was found that the use of an improved method for detecting a low-altitude, low-speed aerial object in the presence of ground clutter using a synchronous multi-radar system has made it possible to increase the signal-to-noise ratio by 4 times.

6. Discussion of results based on the improved method for detecting a low-altitude, low-speed air object

A method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system has been improved, which, in contrast to known ones (for example, [6–9, 16, 17]), allows for the following:

- conducting a synchronous survey of the airspace in azimuth and range by two radars by emitting mutually orthogonal probing signals;
- forming signals reflected from the air object at the output of the radar receivers;
- incoherent, joint processing of signals using a synchronous multi-radar system from two survey radars;
- coordinated filtering of received signals;
- formation of Doppler channels;
- equalization by delay time and Doppler frequency;
- formation of an additive processing channel where incoherent summation of signals is carried out and formation of air object detection marks in the additive channel is carried out;
- formation of a multiplicative processing channel where multiplication of signals is carried out and formation of air object detection marks in the multiplicative channel is carried out;

– combination of air object detection marks in the additive and multiplicative channels and formation of final detection marks.

This becomes possible thanks to the use of a synchronous multiradar system.

An experimental study was conducted on the detection of a low-altitude, low-speed aerial object. The echo signal packets from a low-altitude, low-speed aerial object and from the ground clutter are shown in Fig. 4, 5, respectively. At the MF output, the echo signal packets from a low-altitude, low-speed aerial object and from the ground clutter are shown in Fig. 6, 7, respectively. The echo signals from a low-altitude, low-speed aerial object and from the ground clutter at the output (DF+AD) are depicted in Fig. 8, 9, respectively. Analysis of Fig. 8, 9 reveals that the echo signals from a low-altitude, low-speed aerial object and from the ground clutter are in the same discrete Doppler frequency. This fact is illustrated in Fig. 10.

Echo signals at the output (DF+AD) of RADAR 1 from RADAR 1 and from RADAR 2 are shown in Fig. 11, 12, respectively. Echo signals at the output (DF+AD) of RADAR 2 from RADAR 1 and from RADAR 2 are illustrated in Fig. 13, 14, respectively. Signals at different stages of processing are shown in Fig. 15–17. Analysis of Fig. 17 indicates a clear separation of the signal from a low-altitude, low-speed air object in the presence of ground clutter. To assess the gain in the signal/noise ratio of the improved method, Fig. 18 shows the signals: input (blue color), at the output of the additive processing channel (black color) and at the output of the multiplicative processing channel (red color).

For calculations illustrated in Fig. 18, we used the results from known methods, for example, [6, 7, 10, 13, 16, 17].

From the analysis of Fig. 18, it was established that the use of an improved method for detecting a low-altitude, low-speed air object against the background of reflection from the substratum in a synchronous multiradar system made it possible to increase the signal/noise ratio by 4 times compared to known methods [6, 7, 10, 13, 16, 17]. This became possible thanks to the use of a synchronous multi-radar system.

The improved method for detecting a low-altitude, low-speed air object against the background of reflection from the substratum using a synchronous multi-radar system has made it possible to solve the problematic part, namely, to increase the signal-to-noise ratio by 4 times.

Therefore, the use of a synchronous multi-radar system made it possible to increase the signal-to-noise ratio when detecting a low-altitude, low-speed air object in the presence of ground clutter.

Thus, the uncorrelation of echo signals reflected from the subsurface and received by elements of the multi-radar network determines the possibility of improving the quality of detection of low-speed air objects against the background of reflections from the subsurface. At the same time, the echo signals from the air object and the ground clutter are in the same Doppler filter. An increase in the signal-to-noise ratio is provided due to the incoherent accumulation of signals received in the channels of the system elements (4 reception channels). Additional multiplicative processing of signals provides an additional increase in the signal-to-noise ratio and improves the discrimination of the signal from the air object against the background of the signals from the ground clutter.

Limitations of our study are as follows:

- only reflections from the ground clutter were selected as interfering reflections;

– it was assumed that synchronous airspace surveillance was provided;

– when conducting an experimental study, the number of elements of the multi-radar system was taken to be two radars.

The disadvantages of the study are as follows:

– the complexity of ensuring synchronous operation of the elements of the multi-radar system;

– limitations on the elements of the multi-radar system (two radars).

Further studies should be aimed at devising a method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system with a number of radars exceeding two.

7. Conclusions

1. The key stages in the improved method for detecting a low-altitude, low-speed air object in the presence of ground clutter using a synchronous multi-radar system are:

– conducting a synchronous survey of the airspace in azimuth and range by two radars by emitting mutually orthogonal probing signals;

– forming at the output of the radar receivers of signals reflected from the air object;

– incoherent joint processing of signals using a synchronous multi-radar system from two survey radars;

– coordinated filtering of received signals;

– formation of Doppler channels;

– equalization by delay time and Doppler frequency;

– formation of an additive processing channel, where incoherent summation of signals and formation of air object detection marks in the additive channel are carried out;

– formation of a multiplicative processing channel, where signals are multiplied and air object detection marks of the multiplicative channel are formed;

– combination of air object detection marks of the additive and multiplicative channels and formation of final detection marks.

2. An experimental study has been conducted on the detection of a low-altitude, low-speed air object. The use of a synchronous multiradar system has made it possible to increase the signal/noise ratio by 4 times. Additional multiplicative signal processing provides an additional increase in

the signal/noise ratio and improves the discrimination of the signal from the air object in the presence of ground clutter.

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

The data will be provided upon reasonable request.

Use of artificial intelligence

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

Authors' contributions

Hennadii Khudov: Conceptualization, Methodology, Software, Investigation, Writing – review & editing, Supervision, Project administration; **Andrii Lukianchykov:** Validation, Data curation, Investigation, Software; **Vladyslav Tiutiunnyk:** Validation, Data curation, Writing – original draft, Visualization; **Volodymyr Komarov:** Data curation, Writing – original draft, Visualization; **Oleh Salnyk:** Resources, Writing – review & editing, Funding Acquisition; **Denys Kotov:** Formal analysis, Data curation, Visualization; **Volodymyr Maliuha:** Writing – review & editing, Supervision, Funding acquisition; **Roman Prystynskyi:** Formal analysis, Resources, Visualization; **Valerii Vlasiuk:** Formal analysis, Data curation, Resources, Visualization; **Serhii Popov:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization.

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