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DEVISING A METHOD FOR DETERMINING THE COORDINATES OF AN AIR OBJECT BY A NETWORK OF TWO SDR RECEIVERS

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The object of this study is the process of determining the coordinates of an air object. The main hypothesis of the study assumed that the use of a network of two Software-Defined Radio (SDR) receivers would make it possible to determine the coordinates of an air object. The determined coordinates could be used as preliminary target designation for the radar.

A method for determining the coordinates of an air object by a network of two SDR receivers has been improved, which, unlike the known ones, involves:

– using signals from the airborne systems of the air object;

– using SDR receivers as network elements;

– using the triangulation method for determining the coordinates of an air object.

The accuracy of determining the coordinates of an air object by a network of two SDR receivers has been assessed. It was found that:

– the accuracy of measuring the coordinates of an air object decreases sharply as the polar angle of observation from the middle of the base approaches 0 or π;

– the smallest coordinate measurement error can be ensured when the air object is located on the traverse to the middle of the base and when the distance to the air object is close to the base size;

– with small bases, the non-uniformity of the dependence of the coordinate determination error on the position of the air object relative to the SDR receivers is more pronounced than with large ones;

– at a long range, the error values for small bases grow rapidly, which is primarily due to the small angle of intersection of the bearing lines;

– it is advisable to place SDR receivers at a sufficiently large distance from each other (recommended value: (1–3) times the distance to the air object);

– the errors of measuring the coordinates of the air object have a value of (250–350) m in a sufficiently wide range of directions;

– with a decrease in the base size, the errors grow rapidly (reaching a value of more than 1000 m) when the observation angle deviates from the 90° direction

Keywords: aerial object, SDR receiver network, triangulation method

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1. Introduction

Under current conditions, the design and modernization of air objects significantly outpace the development and modernization of their detection means. The main means of detecting air objects are radars [1]. The capabilities of modern radars to detect and determine the coordinates of modern air objects are significantly limited and do not meet certain requirements [2]. In addition, radars operating under an active location mode are targets for modern means of destruction (for example, anti-radar missiles [3]).

Under such conditions, the most effective way is to use passive location means in general (for example, [4]) and Software-Defined Radio (SDR) receivers (for example, [5]), portable spectrum analyzers (for example, [6]), in particular. Such passive location means have the advantages of an increased signal-to-noise ratio (operating on signals from onboard systems) and, notably, increasing the stealth of their operation.

The main disadvantages of [5, 6] are the use of non-directional antennas and the differential-range-finding method for determining the coordinates of an air object. The use of a non-directional antenna reduces the accuracy of determining the coordinates of an air object. The application of the differential-range-finding method increases the algorithmic complexity of the measurement processing method. This, for example, when using portable spectrum analyzers [6] additionally requires preliminary calculations due to the impossibility of directly coupling a portable spectrum analyzer with a personal computer. Therefore, under modern conditions, especially for detecting military air objects (for example, unmanned aerial vehicles for various purposes [7]), simple, cheap, small-sized passive location devices should be used.

Therefore, devising a method for determining the coordinates of an air object by passive location systems is an urgent task.

2. Literature review and problem statement

In [8], the accuracy of determining the coordinates of an air object is improved by increasing the number of radars. Such an increase in radars improves the accuracy of determining the coordinates of an air object by increasing the number of information sources. However, the issue of ensuring the secrecy of the radar system remains unresolved.

In [9], the secrecy of the radar is ensured by changing the signal frequency. At the same time, the issue of increasing the accuracy of determining the coordinates of an air object remains unresolved.

In [10], increasing the accuracy of determining the coordinates of an air object is assumed by complicating the sounding signal. This, in turn, leads to the use of certain complex algorithms for processing the signal reflected from the air object. The issue of ensuring the secrecy of the radar and increasing the accuracy of detecting the air object.

In [11], combining radars into a network is considered as a way to improve the quality of detection and accuracy of determining the coordinates of an air object. Small-sized radars and coherent processing of signals reflected from the air object are considered. The issues of ensuring the synchronous operation of small-sized radars and ensuring their stealth remain problematic.

In [12], a method of detecting an air object is considered, when in addition to the radar, the use of signals from cellular communication stations is considered. The issues of ensuring the synchronous operation of such a system and ensuring its stealth remain problematic.

In [13], a method for increasing the accuracy of determining the coordinates of an air object is considered, when in addition to the radar, the use of signals from any additional radiation source is considered. The issues of ensuring the synchronous operation of such a system and ensuring the secrecy of its operation remain problematic.

In [14], an increase in the accuracy of determining the coordinates of an air object is assumed due to the complex processing of radar information. This, in turn, leads to the use of certain complex algorithms for processing the signal reflected from the air object. The issues of ensuring the secrecy of the radar operation and increasing the accuracy of detecting an air object are not considered in [14].

In [15], a method for increasing the accuracy of determining the coordinates of an air object is considered, when in addition the use of multilateration technology is proposed in the radar. The issues of practical implementation of methods for processing radar information in such a system and ensuring the secrecy of its operation remain problematic.

In [16], the combination of several radars into a network and additional control of their transmitting and receiving channels is considered as a way to improve the quality of detection and accuracy of determining the coordinates of an air object. The issues of ensuring the coherence of signal processing, ensuring the synchronous operation of radars, and ensuring the secrecy of their operation remain problematic.

In [17], the combination of several (unspecified number) all-round radars into a network is considered as a way to improve the quality of detection and accuracy of determining the coordinates of an air object. The issues of ensuring the coherence of signal processing, ensuring the synchronous operation of radars, and ensuring the secrecy of their operation remain problematic.

Our review of the literature [8–17] revealed that passive location methods are relevant for use. At the same time (especially when conducting combat operations) passive location means should be simple, cheap, small-sized, portable, etc. Therefore, devising a method for determining the coordinates of an air object by passive location systems is an urgent task.

3. The aim and objectives of the study

The purpose of our research is to devise a method for determining the coordinates of an air object by a network of two SDR receivers. This will make it possible, if necessary, to increase the accuracy of determining the coordinates of an air object and, in addition, will ensure the secrecy of the system.

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

– to define the main stages of the method for determining the coordinates of an air object by a network of two SDR receivers;

– to assess the accuracy of determining the coordinates of an air object by a network of two SDR receivers.

4. The study materials and methods

The object of our study is the process of determining the coordinates of an air object.

The main hypothesis of the study assumed that the use of a network of two SDR receivers would make it possible to determine the coordinates of an air object. The determined coordinates could be used as a preliminary target designation for the radar and increase the accuracy of determining the coordinates of an air object. This is especially important under the conditions of modern wars and armed conflicts.

The following research methods were used in the study:

– methods of probability theory and mathematical statistics;

– methods of system analysis;

– mathematical apparatus of matrix theory;

– methods of digital signal processing theory;

– methods of differential calculus;

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

– methods of multi-position radar;

– methods of passive radar;

– methods of mathematical modeling.

The following limitations and assumptions were adopted during the study:

– the network consists of two SDR receivers;

– an aerial object is understood as a low-visibility aerial object, for example, an unmanned aerial vehicle;

– a triangulation method is used to determine the coordinates of an aerial object;

– there are no obstacles to detecting an aerial object;

– reception of the SDR signal by the receivers from the aerial object is ensured;

– SDR receivers are synchronized for operation in the network;

– modeling to assess the accuracy of determining the coordinates of an aerial object by a network of two SDR receivers was carried out using the Monte Carlo statistical test method;

– when conducting mathematical modeling, an unmanned aerial vehicle of the tactical level was used as an aerial object;

– software – multifunctional integrated environment C++ Builder;

– hardware – Dell laptop Intel® Core™ i7-8650U CPU@ 1.90 GHz.

5. Results of the study on devising a method for determining the coordinates of an air object by a network of two SDR receivers

5. 1. The main stages of the method for determining the coordinates of an air object by a network of two SDR receivers

The network of two SDR receivers is shown in Fig. 1.

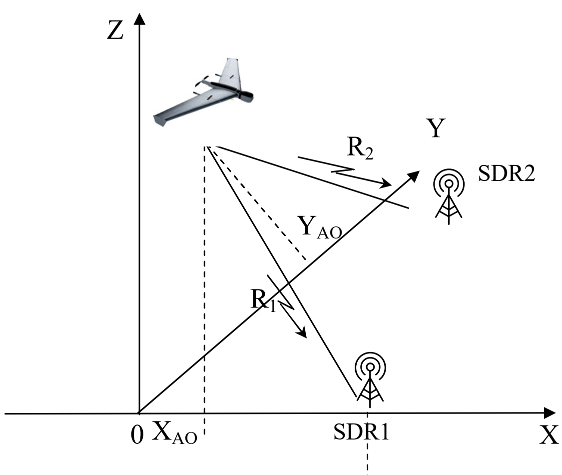

Fig. 1. Network of two SDR receivers

In Fig. 1, a network of two SDR receivers (SDR1, SDR2) measures the coordinates of an air object. The coordinates of the air object (X_{AO}, Y_{AO}) are determined in the 0XY coordinate system.

Signals from the airborne systems of the air object are received by each SDR receiver. Such airborne systems can be, for example, a telemetry system, a target information system, a communication system, etc. Signals from airborne systems are not considered in the work, their characteristics are given in detail, for example, in [5, 18]. The use of signals from airborne systems of the air object increases the accuracy of determining the coordinates of the air object.

Considering that in the SDR receiver network, the methods for determining the coordinates of the air object should be simple, the triangulation method was used [5, 19, 20].

The location of the aerial object is determined by the angular directions to the radiation source measured by two SDR receivers (SDR1, SDR2), by solving the triangulation problem (Fig. 2). The calculation is performed in the rectangular coordinate system 0XY (Fig. 2).

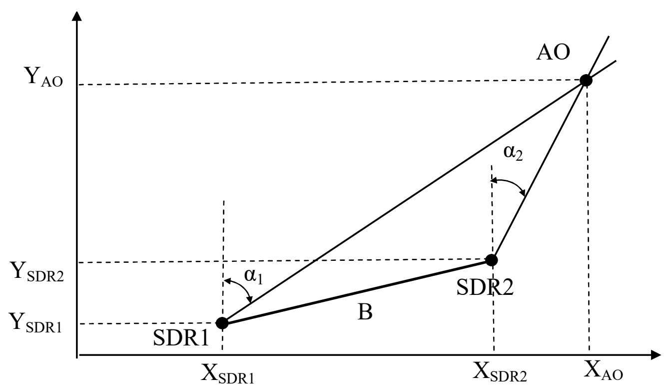

Fig. 2. Triangulation method for determining the coordinates of an aerial object using a network of two SDR receivers

The basic stages of triangulation determination of the coordinates of an aerial object by a network of two SDR receivers are as follows (Fig. 3):

1. Input of initial data: type of SDR receivers, coordinates of SDR receivers x_{SDR1}, y_{SDR1}, x_{SDR2}, y_{SDR2}.

2. Measurement of bearings (by the first SDR receiver (α_1) and the second SDR receiver (α_2)).

3. Determination of the X_{AO} coordinate from expression (1):

$$x_{AO} = \frac{X_{SDR2}\sin\alpha_2 - Y_2\cos\alpha_2}{\sin(\alpha_2 - \alpha_1)}\cos\alpha_1. \quad (1)$$

4. Determination of the Y_{AO} coordinate from expression (2):

$$y_{AO} = \frac{X_{SDR2}\sin\alpha_2 - Y_{SDR2}\cos\alpha_2}{\sin(\alpha_2 - \alpha_1)}\sin\alpha_1. \quad (2)$$

5. Determination of the D_{UAV} range from expression (3):

$$D_{AO} = \frac{X_{SDR2}\sin\alpha_2 - Y_{SDR2}\cos\alpha_2}{\sin(\alpha_2 - \alpha_1)}. \quad (3)$$

6. Checking the location of the air object in the coverage area of the SDR receiver network.

7. When the air object is in the coverage area of the SDR receiver network, the coordinates of the air object are updated.

8. Otherwise, the flight path of the air object is determined.

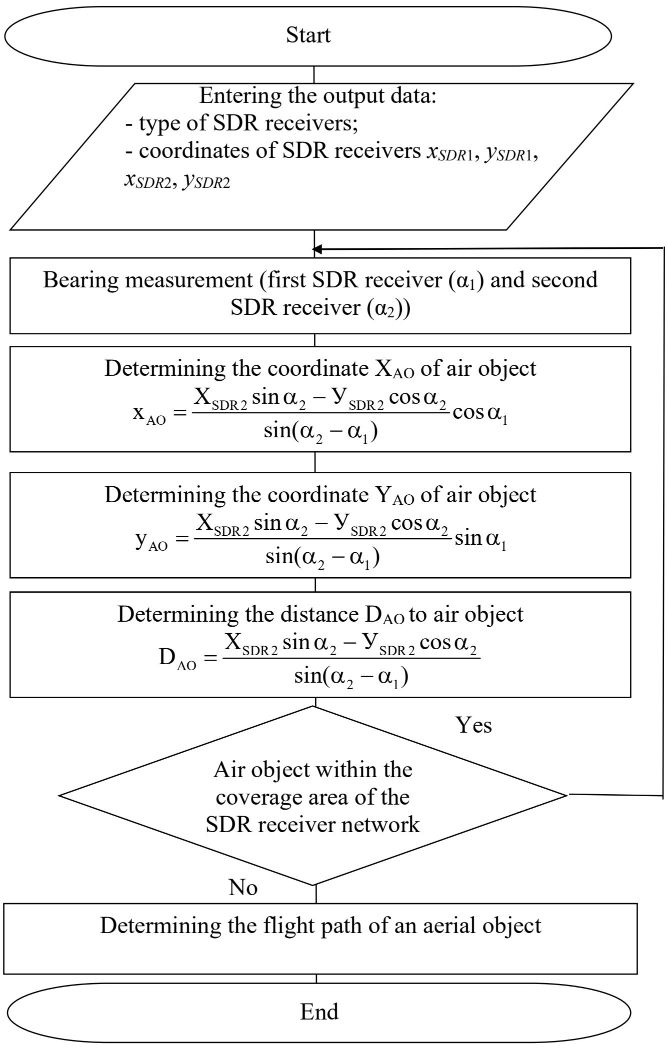

Fig. 3. Basic stages of triangulation determination of the coordinates of an aerial object by a network of two SDR receivers

So, a method of determining the coordinates of an air object by a network of two SDR receivers has been improved, which, unlike known ones, provides for the following:

– using signals from the on-board systems of the air object;

– using SDR receivers as network elements;

– using the triangulation method for determining the coordinates of the air object.

5. 2. Assessing the accuracy of determining the coordinates of an air object by a network of two SDR receivers

The assessment of the accuracy of determining the coordinates of an air object by a network of two SDR receivers was carried out by mathematical modeling using the Monte Carlo statistical test method.

When conducting mathematical modeling, the following restrictions and assumptions were adopted:

– the network consists of two SDR receivers;

– an unmanned aerial vehicle is accepted as the air object;

– the value of the base B (the distance between the SDR receivers) can vary from zero to 3 km;

– the distance between the midpoint of the base and the location of the air object does not exceed 7 km;

– direction finding of the air object is carried out only in coordinates since the flight altitude of the air object is usually typical and, in addition, cannot be accurately determined without the use of antennas with high angular selectivity in terms of elevation angle;

– it is assumed that in SDR receivers have the same antenna systems;

– the errors of direction finding by SDR receivers are caused by the influence of one set of factors, and are distributed according to the normal law;

– the systematic error of direction finding by SDR receivers is zero;

– the root-mean-square deviation of the error of direction finding by SDR receivers σ is determined by the width of the antenna directional pattern in azimuth $\Delta\theta_{0.5}$ and is calculated from expression (4):

$$\sigma=0.2\ \Delta\theta_{0.5}; \quad (4)$$

– there are no obstacles to detecting an aerial object;

– reception of the SDR signal by receivers from the aerial object is ensured;

– SDR receivers are synchronized for operation in the network;

– the Monte Carlo statistical testing method is used;

– software – multifunctional integrated environment C++ Builder;

– hardware – Dell Intel® Core™ i7-8650U CPU@ 1.90 GHz laptop.

The process of measuring the coordinates of the aerial object was modeled as follows. For the selected position of the aerial object, the true bearings α_1 and α_2 were calculated from expression (5):

$$\alpha_i = \mathrm{arctg}\left(\frac{X_{AO}-X_i}{Y_{AO}-Y_i}\right),\ i=1,2. \quad (5)$$

Next, to obtain the measured value ($\hat{\alpha}_i$, i=1,2) the measurement error was added to the calculated value of the true bearing. As the measurement error, a random variable distributed according to the normal law with a mathematical expectation m=0 and a standard deviation σ was used. To generate the random variable, the built-in function $Rand(G(m,\sigma))$ with the corresponding parameters (expression(6)) was used:

$$\hat{\alpha}_i = \alpha_i + Rand\big(G(0,\sigma)\big),\ i=1,2. \quad (6)$$

For the obtained values ($\hat{\alpha}_i$, i=1,2), the measured coordinates of the air object $\hat{X}_{AO}$ and $\hat{Y}_{AO}$. were calculated using expressions (1), (2). The errors of measuring the coordinates σ_X and σ_Y were calculated as the mean square deviation of the values $\left(\hat{X}_{AO}-X_{AO}\right)$ and $\left(\hat{Y}_{AO}-Y_{AO}\right)$, respectively ($X_{AO}$, Y_{AO} – the true values of the coordinates of the air object). The total mean square error was calculated using expression (7):

$$\sigma=\sqrt{\sigma_X^2+\sigma_Y^2}. \quad (7)$$

The results of modeling are shown in Fig. 4, 5.

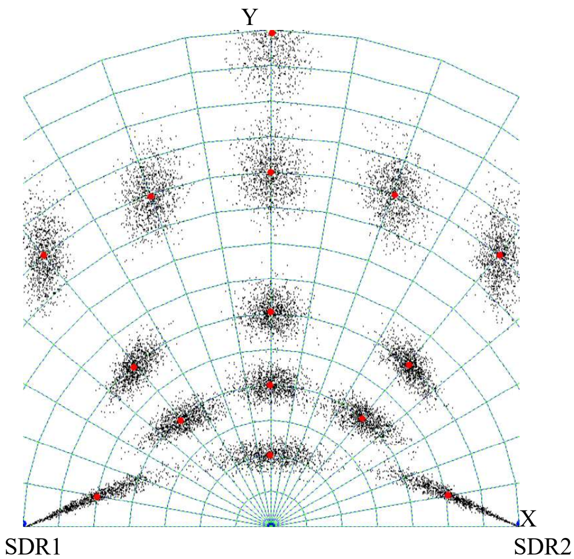

Fig. 4. Errors in determining coordinates by a network of two SDR receivers (the distance between the direction finding points is 7 km, the root mean square error of the bearing measurement for both points is 2.5°)

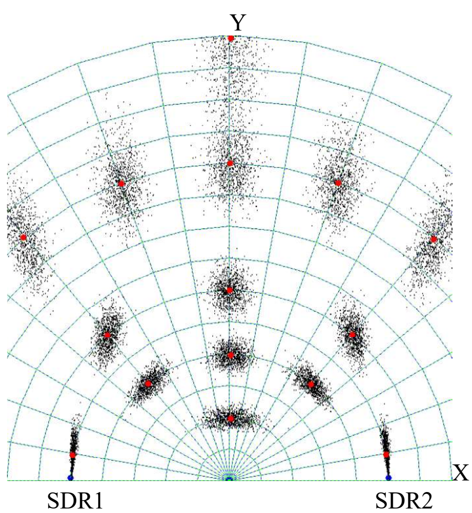

Fig. 5. Errors in determining coordinates by a network of two SDR receivers (the distance between the direction finding points is 5 km, the root mean square error of the bearing measurement for both points is 2.5°)

The dimensions in Fig. 4, 5 correspond to the linear size of 7×7 km., the range grid step is 500 meters, the azimuth grid – 10°.

Fig. 4 corresponds to the situation when SDR receivers (blue dots) are located at a distance of 7 km from each other. In this case, there is no systematic error component. The value of the bearing measurement error for both SDR receivers is the same and distributed according to the normal law with zero mathematical expectation and a mean square error of 2.5°.

This value corresponds to the case of using weakly directional antennas for direction finding by the maximum method and the arrival of the signal source at a short distance, which provides sufficiently large values of the signal/noise ratio at the receiving point.

The simulation conditions for Fig. 5 differ in the smaller distance between SDR receivers, which is 5 km.

The considered cases correspond to most practical situations of using a network of SDR receivers under field conditions.

In Fig. 4, 5, the red dots show the true position of the air object, the black dots show the position corresponding to the results of determining the coordinates by the triangulation method. The number of measurements for each point is 1000, which make it possible to estimate the configuration of the error ellipse and estimate the value of the average circular error in determining the coordinates of the air object with reasonable accuracy for practice.

From the analysis of Fig. 4, 5, it follows that the shape and size of the scattering ellipse depends on the position of the air object in space relative to the SDR receivers and is similar for both cases (Fig. 4, 5).

The accuracy of measuring the coordinates of the air object decreases sharply when the polar angle of observation from the middle of the base approaches 0 or π. This is explained by the fact that under such conditions, even small errors in direction finding cause significant deviations of the point of intersection of the azimuthal lines of position from the true position of the air object.

Studies have shown that the smallest coordinate measurement error can be ensured when the aerial object is located on the traverse to the middle of the base (the observation angle from the middle of the base is 90°) and when the distance to the aerial object is close to the size of the base.

At small bases, the non-uniformity of the dependence of the error in determining the coordinates on the position of the air object relative to the SDR receivers is more pronounced than at large ones. At long ranges, the error values at small bases grow rapidly, which is primarily due to the small angle of intersection of the bearing lines.

For practical use, the following recommendations can be formulated. SDR receivers should be placed at a sufficiently large distance from each other (recommended value: (1–3) times the distance to the air object).

In this case, the angles of convergence of the bearings are close to 90° in a sufficiently large area of space. The errors in measuring the coordinates of the air object take values that are acceptable for practical use. They are (250–350) m in a sufficiently wide range of directions (the observation angle from the middle of the base is (30°–60°)). When the base size decreases, the errors increase rapidly (reaching values greater than 1000 m) when the observation angle deviates from the 90° direction.

6. Discussion of results based on improving the method for determining the coordinates of low-visibility air objects

A network of two SDR receivers (Fig. 1) has been considered. Signals from the airborne systems of the air object are received by each SDR receiver. Such airborne systems can be, for example, a telemetry system, a target information system, a communication system, etc.

Considering that in the network of SDR receivers the methods for determining the coordinates of an air object should be simple, the triangulation method was used (Fig. 2).

The method for determining the coordinates of an air object by a network of two SDR receivers has been improved, which, unlike known ones (for example, [5, 19, 20], provides for the following:

– the use of signals from airborne systems of an air object;

– the use of SDR receivers as network elements;

– the use of the triangulation method for determining the coordinates of an air object.

The accuracy of determining the coordinates of an air object by a network of two SDR receivers has been assessed. The accuracy was assessed by mathematical modeling using the Monte Carlo statistical test method. The modeling results are shown in Fig. 4, 5.

Fig. 4 corresponds to a situation when SDR receivers (blue dots) are located at a distance of 7 km from each other. In this case, there is no systematic error component. The value of the bearing measurement error for both SDR receivers is the same and distributed according to a normal law with a zero mathematical expectation and a root-mean-square error of 2.5°.

This value corresponds to the case of using weakly directional antennas for direction finding by the maximum method and the arrival of the signal source at a short distance, which provides sufficiently large values of the signal/noise ratio at the receiving point.

The simulation conditions for Fig. 5 differ in the smaller distance between the SDR receivers, which is 5 km.

From the analysis of Fig. 4, 5 it follows that the shape and size of the scattering ellipse depends on the position of the air object in space relative to the SDR receivers and is similar for both cases (Fig. 4, 5).

The accuracy of measurements of the coordinates of the air object decreases sharply when the polar angle of observation from the middle of the base approaches 0 or π. Studies have shown that the smallest error in measuring coordinates can be ensured when the air object is located on the traverse to the middle of the base (the angle of observation from the middle of the base is 90°) and when the distance to the air object is close to the size of the base.

At small bases, the non-uniformity of the dependence of the error in determining the coordinates on the position of the air object relative to the SDR receivers is more pronounced than at large ones. At long ranges, the error values at small bases grow rapidly, which is primarily due to the small angle of intersection of the bearing lines.

From the analysis of Fig. 4, 5 it has been established that it is advisable to place SDR receivers at a sufficiently large distance from each other (recommended value: (1–3) times the distance to the aerial object). In this case, the errors in measuring the coordinates of the aerial object take a value of ((250–350) m) in a sufficiently wide range of directions. When the base value decreases, the errors increase rapidly (reaching a value of more than 1000 m) when the observation angle deviates from the 90° direction.

The limitations of our method are:

– it is used only for detecting and measuring the coordinates of air objects;

– the method is applicable only for a network of SDR receivers;

– the influence of electronic warfare is not taken into account.

The disadvantage of the method is the use of only two SDR receivers, which may limit the required accuracy in determining the coordinates of an air object for certain cases.

Further research is aimed at investigating the possibility of determining the coordinates of an air object by a network with a larger number of SDR receivers.

7. Conclusions

1. The main stages of the method for determining the coordinates of an air object by a network of two SDR receivers:

– input of initial data: type of SDR receivers, coordinates of SDR receivers;

– measurement of bearings by the first and second SDR receivers;

– determination of the coordinates of the air object and the distance to the air object;

– checking the location of the air object in the coverage area of the SDR receiver network;

– determination of the flight trajectory of the air object.

2. The accuracy of determining the coordinates of an air object by a network of two SDR receivers has been assessed. It was found that:

– the accuracy of measuring the coordinates of an air object decreases sharply when the polar angle of observation from the middle of the base approaches 0 or π;

– the smallest error in measuring coordinates can be ensured when the air object is located on the traverse to the middle of the base and when the distance to the air object is close to the size of the base;

– at small bases, the unevenness of the dependence of the error in determining coordinates on the position of the air object relative to the SDR receivers is more pronounced than at large ones;

– at long ranges, the error values at small bases increase rapidly, which is primarily due to the small angle of intersection of the bearing lines;

– it is advisable to place SDR receivers at a sufficiently large distance from each other (recommended value: (1–3) the size of the distance to the air object);

– errors in measuring the coordinates of an aerial object take a value of ((250–350) m) in a fairly wide range of directions;

– when the base size decreases, the errors increase rapidly (reaching a value of more than 1000 m) when the observation angle deviates from the 90° direction.

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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