The object of this study is the process of determining the coordinates of an unmanned aerial vehicle. The main hypothesis of the study assumed that the use of a network of three Software-Defined Radio (SDR) receivers could improve the accuracy of determining the coordinates of an unmanned aerial vehicle. The use of SDR receivers in pairs would reduce the number of false bearings.

A method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when used in pairs has been improved, which, unlike the known ones, involves:

– measuring bearings by each SDR receiver;

– determining the pairwise angles of intersection of bearings;

– determining the maximum of the pairwise angles of intersection;

– determining a pair of SDR receivers for further calculations;

– using the triangulation method for determining the coordinates of an unmanned aerial vehicle.

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

– the shape, orientation, and size of the error ellipses depend on the relative location in space of the SDR receivers and the unmanned aerial vehicle;

– the size of the scattering ellipses is reduced by (20–40) % due to the use of information from the optimal pair;

– in some cases, false switching of SDR receiver pairs is noticeable;

– the pair (first SDR receiver – third SDR receiver) has the largest base from the considered options, that is, starting from a certain range, the angle of intersection of the bearings for this case is closest to 90°, the area of the scattering ellipses of coordinate measurement errors is minimal, which determines its choice;

– when moving the unmanned aerial vehicle beyond the network coverage area of the SDR receiver pair, it is advisable to use another pair, this involves the use of a "chain" of SDR receivers

Keywords: unmanned aerial vehicle, paired use of SDR receivers, bearing intersection angle

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DEVISING A METHOD FOR DETERMINING THE COORDINATES OF AN UNMANNED AERIAL VEHICLE BY A NETWORK OF THREE SOFTWARE-DEFINED-RADIO RECEIVERS USED IN PAIRS

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1. Introduction

The world experience in the development of aerial objects, especially for security and defense, is primarily associated with the design of unmanned aerial vehicles [1, 2]. Such unmanned aerial vehicles are atypical objects (targets) for modern airspace control radars [3]. In addition, due to their speed, for example, the unmanned aerial vehicle "Orlan-10"

(Russian Federation), falls into the range of radar passive interference protection systems [4]. The decrease in the speed of unmanned aerial vehicles, in comparison with typical radar targets, causes the rejection of signals from unmanned aerial vehicles (UAVs) in moving target selection systems together with reflections from local objects. Therefore, unmanned aerial vehicles are difficult targets for existing radars and are more often not observed on radar indicator screens. Also, the active mode of operation of modern radars is their main unmasking feature. Therefore, under conditions of military conflicts and wars, radars are priority targets for destruction [5]).

To prevent the above, specialists use means of detecting unmanned aerial vehicles by their own radiation. Such means include, for example, portable spectrum analyzers [6] and Software-Defined Radio (SDR) receivers [7].

The main disadvantage of using a network consisting of only two devices (two SDR receivers or two portable spectroanalyzers) is the low accuracy of detecting an unmanned aerial vehicle. Moreover, the accuracy is low not in the entire network coverage area but in certain areas. An increase in the number of passive location devices leads to an increase in the accuracy of determining the coordinates of an unmanned aerial vehicle. At the same time, this leads to the appearance of false bearings, which significantly reduces the efficiency of the passive location system.

Therefore, it would be advisable to increase the number of passive location devices in the network but to use a simple triangulation method to determine the coordinates of an unmanned aerial vehicle [8]. This could eliminate the appearance of false bearings and ensure the use of cheap, simple, small-sized devices.

Therefore, devising a method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when they are used in pairs is an urgent task.

2. Literature review and problem statement

A conventional method for increasing the accuracy of determining the coordinates of an unmanned aerial vehicle is to use several radars (for example, [9]). At the same time, when an unmanned aerial vehicle is in the range of local objects of one radar, other radars have the ability to detect such an unmanned aerial vehicle. The disadvantages of [9] are the increase in the cost of the radar system and ensuring their stealth.

A method for changing the frequency of the sounding signal is proposed in [10]. This method increases the stealth of the radar but the problem of low accuracy of detecting an unmanned aerial vehicle remains.

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 unmanned aerial vehicle. In this case, only two-coordinate radars are considered, which have low accuracy indicators. The issue of ensuring the synchronous operation of two-coordinate radars remains problematic.

In [12], a method for increasing the accuracy of determining the coordinates of an unmanned aerial vehicle is considered; in addition to radar, the use of signals from cellular communication stations is suggested. The issues of ensuring the synchronous operation of such a system and ensuring the secrecy of its operation remain problematic.

In [13], a method for increasing the accuracy of determining the coordinates of an unmanned aerial vehicle is considered; in addition to the radar, the use of signals from space navigation systems is proposed. The issues of ensuring the synchronous operation of such a system and ensuring the secrecy of its operation remain problematic.

In [14], the process of planning the flight trajectory of an unmanned aerial vehicle is considered. A mathematical model for intelligent planning of the flight trajectory of an unmanned aerial vehicle is built. It is established that for high-quality detection of an unmanned aerial vehicle and measurement of its coordinates by radar, it is necessary to take into account the adaptability of the movement of the unmanned aerial vehicle. However, in [14], the issue of increasing the accuracy of determining the coordinates of an unmanned aerial vehicle is not considered.

In [15], the formation of the radar detection zone with the additional use of any radiation source is considered. It is established that with the additional use of any radiation source, the compatible detection zone of such a system decreases. This affects the accuracy of determining the coordinates of the unmanned aerial vehicle.

In [16], a method for increasing the accuracy of determining the coordinates of an unmanned aerial vehicle is considered; in addition to radar, the use of a multilateration system is suggested. The issues of enabling the synchronous operation of such a system and ensuring the secrecy of its operation remain problematic.

A method for increasing the accuracy of an unmanned aerial vehicle is proposed in [17]. The method involves controlling the transmitting and receiving channels of the radar. In this case, the radars are additionally combined into a network. The disadvantage of [17] is the incoherence of processing and ensuring the synchronous operation of the radars.

The use of a radar network is also proposed in [18]. Such a combination increases the accuracy of determining the coordinates of an unmanned aerial vehicle. The disadvantage of [18] is the incoherence of processing and ensuring the synchronous operation of the radars.

Our review of the literature [9–19] reveals certain shortcomings of known methods for increasing the accuracy of determining the coordinates of an unmanned aerial vehicle. To avoid the main disadvantages of using passive location methods, the use of passive location tools and methods is proposed. In this case, it is advisable to increase the number of mobile, portable passive location tools, and combine them into a network. Therefore, devising a method for determining the coordinates of an unmanned aerial vehicle by a network of passive location tools 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 unmanned aerial vehicle using a network of three SDR receivers when used in pairs. This will make it possible to improve the accuracy of determining the coordinates of an unmanned aerial vehicle and reduce the number of false bearings.

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

– to list the main stages of the method for determining the coordinates of an unmanned aerial vehicle using a network of three SDR receivers when used in pairs;

– to assess the accuracy of determining the coordinates of an unmanned aerial vehicle using a network of three SDR receivers when used in pairs.

4. The study materials and methods

The object of our study is the process of determining the coordinates of an unmanned aerial vehicle.

The main hypothesis of the study assumed that the use of a network of three SDR receivers would improve the accuracy of determining the coordinates of an unmanned aerial vehicle. In addition, the use of SDR receivers in pairs could reduce the number of false bearings. This is especially important when determining the coordinates of an unmanned aerial vehicle.

The following research methods were used in the study:
– radar methods;
– multi-position radar methods;
– passive radar methods;
– mathematical apparatus of matrix theory;
– methods of system analysis;
– methods of statistical theory for detection and measurement of radar signal parameters;
– methods of digital signal processing theory;
– methods of probability theory and mathematical statistics;
– methods of mathematical modeling.

The following limitations and assumptions were adopted during the study:
– the number of SDR receivers in the network is three;
– when determining the coordinates of an unmanned aerial vehicle, measurements of only two SDR receivers are analyzed;
– the triangulation method for determining the coordinates of an unmanned aerial vehicle is considered;
– there are no obstacles when measuring the coordinates of an unmanned aerial vehicle;
– each SDR receiver receives a signal from an unmanned aerial vehicle;
– three SDR receivers are located on the same line;
– synchronization of SDR receivers is ensured;
– the Monte Carlo method (statistical tests) is used;
– in calculations (modeling), the reconnaissance unmanned aerial vehicle "Orlan-10" (Russian Federation) is considered;
– software – multifunctional integrated environment C++ Builder;
– hardware – Dell laptop Intel® Core™ i7-8650U CPU@ 1.90 GHz.

5. Results of the study related to devising a method for determining the coordinates of an unmanned aerial vehicle

5. 1. Main stages of the method for determining the coordinates of an unmanned aerial vehicle

A network of three SDR receivers located on the same line is shown in Fig. 1.

Three SDR receivers ((SDR1, SDR2, SDR3) receive a signal from an unmanned aerial vehicle. The signal sources are the on-board systems of the unmanned aerial vehicle [4, 19]. SDR receivers measure the coordinates of the unmanned aerial vehicle in a Cartesian coordinate system. The coordinates of the unmanned aerial vehicle are denoted (X_{UAV}, Y_{UAV}).

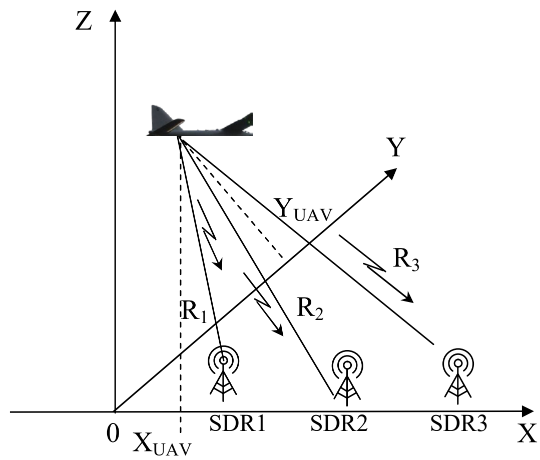

Fig. 1. Network of three SDR receivers located along the same line

Taking into account the simplicity of implementation, the triangulation method was chosen to determine the coordinates of the unmanned aerial vehicle [7, 20]. The triangulation method is used by searching through pairs of SDR receivers.

When using (processing) data from three SDR receivers and two unmanned aerial vehicles simultaneously, false bearings and ambiguity in determining the coordinates of the unmanned aerial vehicle appear (Fig. 2).

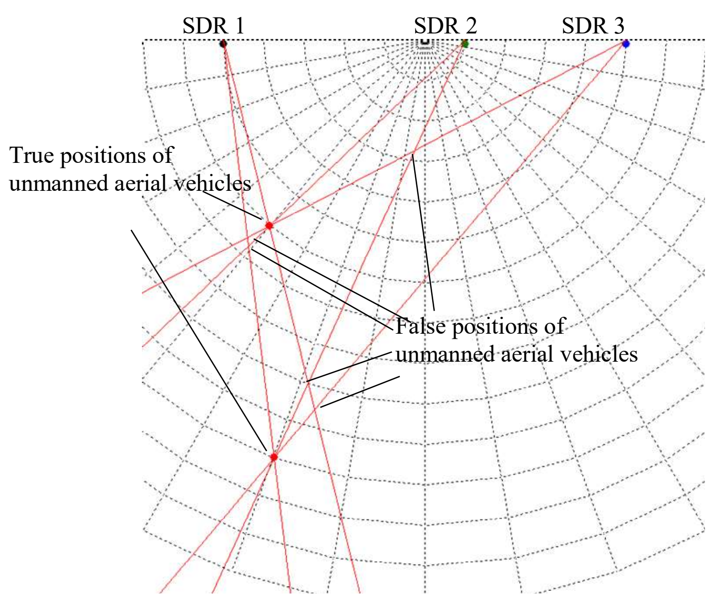

Fig. 2. True and false bearings when using data from three SDR receivers and two unmanned aerial vehicles simultaneously

In [21] it is stated that the ellipse of dispersion of errors of determination of coordinates has the minimum area when the unmanned aerial vehicle is located at the point where the angle of intersection of bearings is close to 90°.

This fact was used to select a pair of SDR receivers. The selection of a pair of SDR receivers provided the most accurate determination of the coordinates of the unmanned aerial vehicle and the selection (reduction) of false bearings.

Taking into account the above, the main stages of the method for determining the coordinates of the unmanned aerial vehicle by a network of three SDR receivers when they are used in pairs are as follows (Fig. 3):

1. Input of initial data: coordinates of three SDR receivers of the network (x_{SDR1}, y_{SDR1}), (x_{SDR2}, y_{SDR2}), (x_{SDR3}, y_{SDR3}), type of SDR receivers in the network.

2. Measurement of bearings by each SDR receiver (first SDR receiver (α_1), second SDR receiver (α_2), third SDR receiver (α_3)).

3. Determining the angles of intersection of bearings (pairwise) (angle of intersection of the first and second bearings ($\angle(\alpha_1,\alpha_2)$); angle of intersection of the first and third bearings ($\angle(\alpha_1,\alpha_3)$); angle of intersection of the second and third bearings ($\angle(\alpha_2,\alpha_3)$).

4. Determining the maximum of the pairwise angles of intersection (expression (1)):

$$\max\left(\angle\left(\alpha_i,\alpha_j\right)\right),\ \left(i \neq j\right). \quad (1)$$

5. Determining a pair of SDR receivers for further calculations (SDR_i, SDR_j).

6. Determining the coordinates of the unmanned aerial vehicle (X_{UAV}, Y_{UAV}) and the range to it D_{UAV} using expressions (2) to (4) (Fig. 4 [21]):

$$x_{UAV} = \frac{X_{SDRj}\sin\alpha_j - Y_{SDRj}\cos\alpha_j}{\sin\left(\alpha_j - \alpha_i\right)}\cos\alpha_i. \quad (2)$$

$$x_{UAV} = \frac{X_{SDRj}\sin\alpha_j - Y_{SDRj}\cos\alpha_j}{\sin\left(\alpha_j - \alpha_i\right)}\cos\alpha_i. \quad (3)$$

$$D_{UAV} = \frac{X_{SDRj}\sin\alpha_j - Y_{SDRj}\cos\alpha_j}{\sin\left(\alpha_j - \alpha_i\right)}. \quad (4)$$

7. Checking the condition of the unmanned aerial vehicle being in the coverage area of the network of three SDR receivers.

8. When the unmanned aerial vehicle is in the coverage area of the network of three SDR receivers, the coordinates of the unmanned aerial vehicle are updated.

9. Otherwise, the flight trajectory of the unmanned aerial vehicle is determined.

Thus, a method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when used in pairs has been improved, which, unlike the known ones, provides for the following:

– measuring bearings by each SDR receiver;

– determining pairwise angles of intersection of bearings;

– determining the maximum of pairwise angles of intersection;

– determining a pair of SDR receivers for further calculations;

– using the triangulation method for determining the coordinates of an unmanned aerial vehicle.

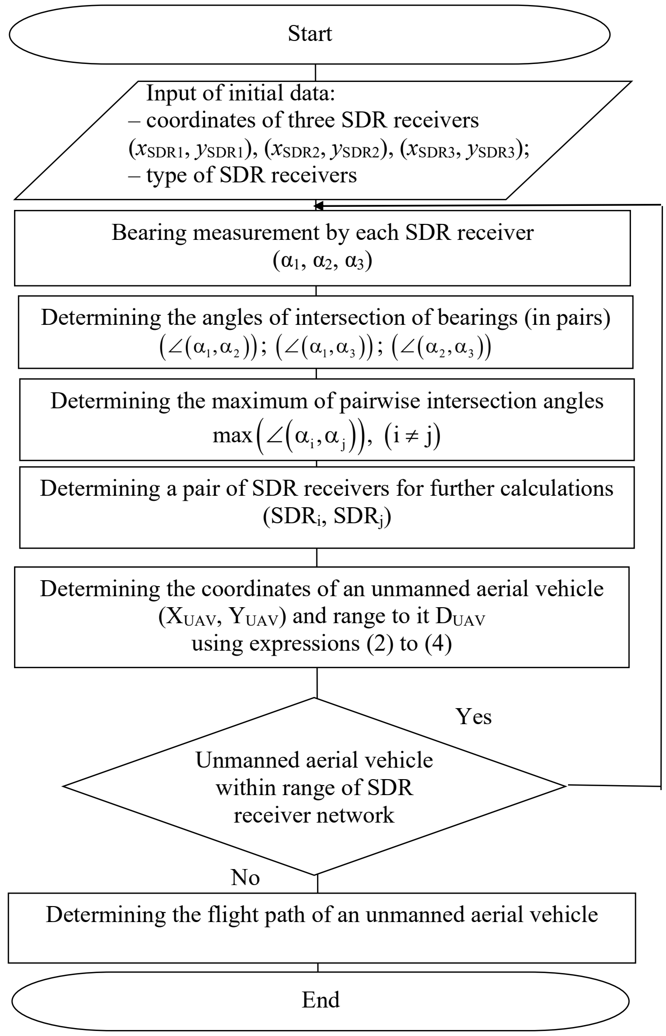

Fig. 3. Main stages of the method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when used in pairs

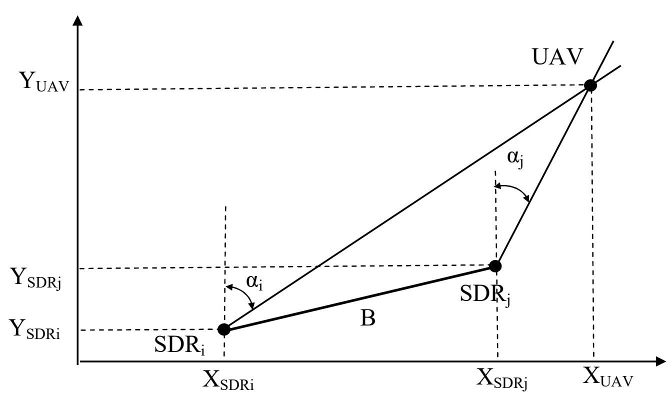

Fig. 4. Determining the coordinates of an unmanned aerial vehicle by a specified pair of SDR receivers (SDR_i, SDR_j)

5. 2. Assessing the accuracy of determining the coordinates of an unmanned aerial vehicle

The assessment of the accuracy in determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when they are used in pairs was carried out by mathematical modeling. The Monte Carlo statistical testing method was used.

The mathematical modeling involved the adoption of certain restrictions and assumptions:

– number of SDR receivers in the network – three;

– when determining the coordinates of an unmanned aerial vehicle, measurements of only two SDR receivers are analyzed;

– the triangulation method for determining the coordinates of an unmanned aerial vehicle is considered;

– there are no obstacles when measuring the coordinates of an unmanned aerial vehicle;

– each SDR receiver receives a signal from an unmanned aerial vehicle;

– three SDR receivers are located along the same line;

– the first SDR receiver is marked in black, the second SDR receiver is marked in green, the third SDR receiver is marked in blue;

– the distance between the first SDR receiver and the second SDR receiver is 3 km, between the first SDR receiver and the third SDR receiver is 5 km;

– the distances between the SDR receivers are chosen not to be multiples of each other, this is done intentionally to avoid a possible moiré effect;

– the true position of the unmanned aerial vehicle is marked in red;

– synchronization of SDR receivers is ensured;

– the reconnaissance unmanned aerial vehicle "Orlan-10" (Russian Federation) is considered;

– the antenna systems of the three SDR receivers are identical;

– the errors in determining the coordinates by each SDR receiver are distributed according to the normal (Gaussian) law;

– the width of the antenna directivity diagram in azimuth $\Delta\theta_{0,5}$ determines the root-mean-square error σ in determining the coordinates of the unmanned aerial vehicle of each SDR receiver (expression (5) [21]):

$$\sigma=0.2\ \Delta\theta_{0.5}; \tag{5}$$

– simulation area – area of space (7×7) km;

– grid step in range corresponds to 500 m;

– grid step in azimuth – 10°;

– software – multifunctional integrated environment C++ Builder;

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

The process of modeling the measurement of the coordinates of an unmanned aerial object was carried out according to the methodology from [21].

The results of modeling the determination of the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the second SDR receiver are shown in Fig. 5. The results of modeling the determination of the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the third SDR receiver are shown in Fig. 6. The results of modeling the determination of the coordinates of an unmanned aerial vehicle for the case of using the second SDR receiver and the third SDR receiver are shown in Fig. 7.

The red dots show the true position of the unmanned aerial vehicle, the green and blue ones show the position corresponding to the results of determining the plane coordinates by the triangulation method. The number of measurements for each point is 1000, which allows us to estimate the configuration and size of the coordinate determination error zone with sufficient accuracy for practice. From the analysis of Fig. 5–7 it is clear that the shape, orientation, and size of the error ellipses depend on the relative location in space of the SDR receivers and the unmanned aerial vehicle.

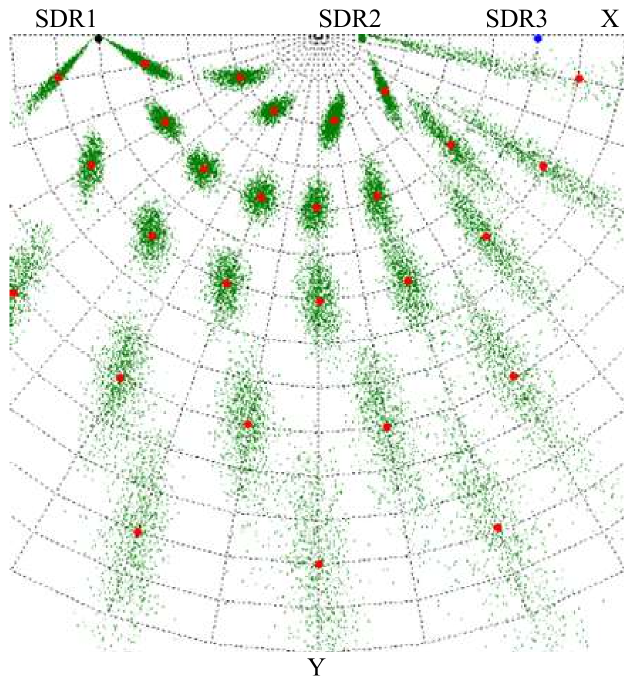

Fig. 5. Simulation results of determining the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the second SDR receiver

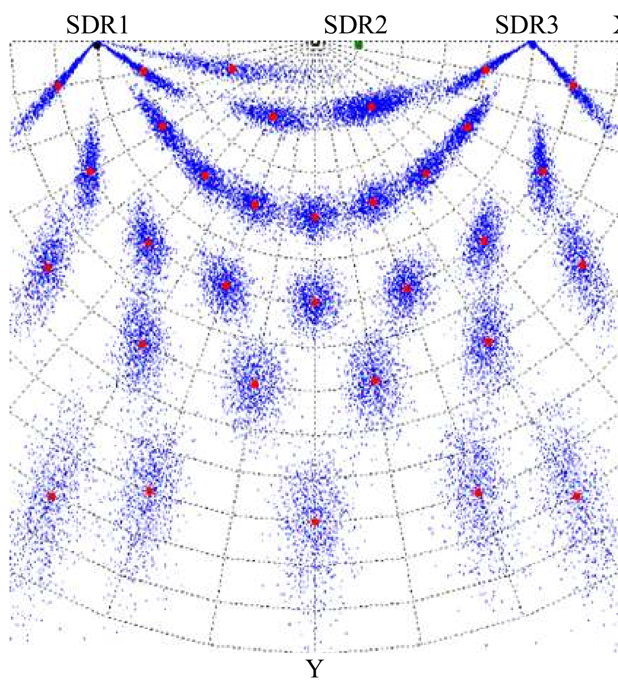

Fig. 6. Simulation results of determining the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the third SDR receiver

Fig. 8, 9 show the results of modeling when using SDR receivers in pairs with the selection of the optimal pair of SDR receivers. Thus, Fig. 8 shows the results of modeling when using the first SDR receiver and the second SDR receiver and the first SDR receiver and the third SDR receiver in pairs. The corresponding zones are colored to show the selection of the optimal pair of SDR receivers.

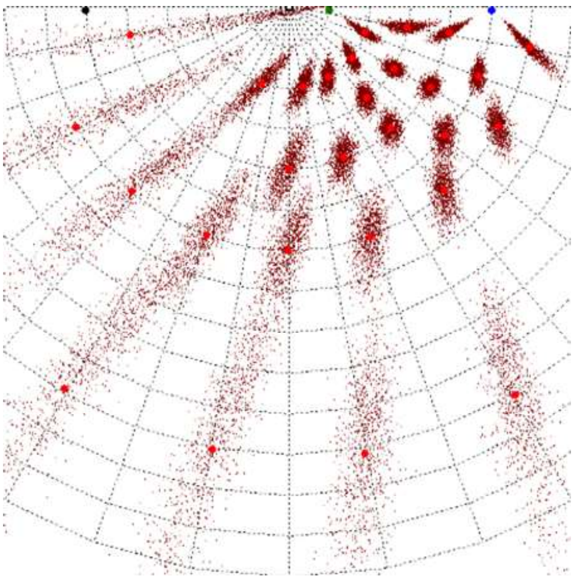

Fig. 7. Simulation results of determining the coordinates of an unmanned aerial vehicle for the case of using a second SDR receiver and a third SDR receiver

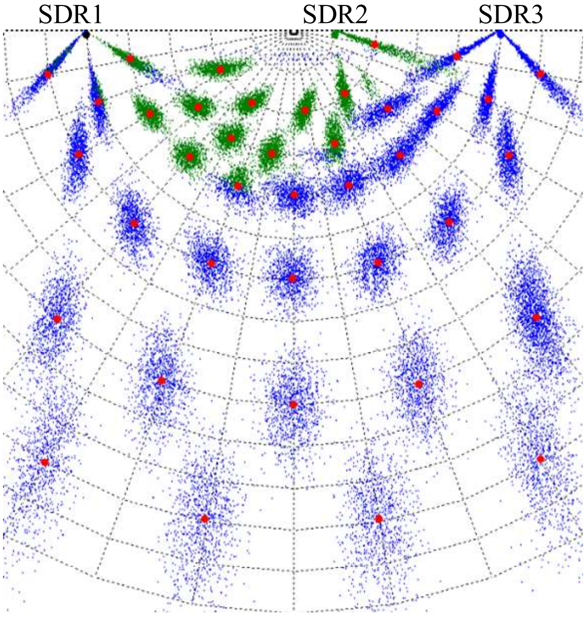

Fig. 8. Simulation results of determining the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the second SDR receiver; the first SDR receiver and the third SDR receiver with the selection of the optimal pair

In each iteration of the simulation, the angles of intersection of the bearings were calculated for each pair of SDR receivers; for further calculations, the pair of SDR receivers was selected for which the angle of intersection of the bearings was closest to 90°.

The calculated point of the position of the unmanned aerial vehicle was marked in different colors. Green – in the case of using the information of the pair (the first SDR receiver – the second SDR receiver). Blue – in the case of using the information of the pair (the first SDR receiver and the third SDR receiver).

The analysis of Fig. 8 reveals a decrease in the size of the scattering ellipses (the error in measuring the coordinates of the unmanned aerial vehicle) by (20–40) % due to the use of the information of the optimal pair for calculating the coordinates. In the area opposite the third SDR receiver and to the left of it, false positives are observed due to the fact that the angles of intersection of the bearings are close to acute. Analysis of Fig. 8 reveals that when finding an unmanned aerial vehicle between the first SDR receiver and the second SDR receiver, information from them is used up to a certain distance, which corresponds to the theoretically obtained results. For the pair (first SDR receiver – third SDR receiver), the angles of intersection of the bearings are sharper, which leads to larger errors in determining the coordinates. In some cases, false switching of pairs of SDR receivers is noticeable. This is due to the fact that for both cases the angles of intersection of the bearings are close in value and due to errors in determining the bearings there is a certain randomness.

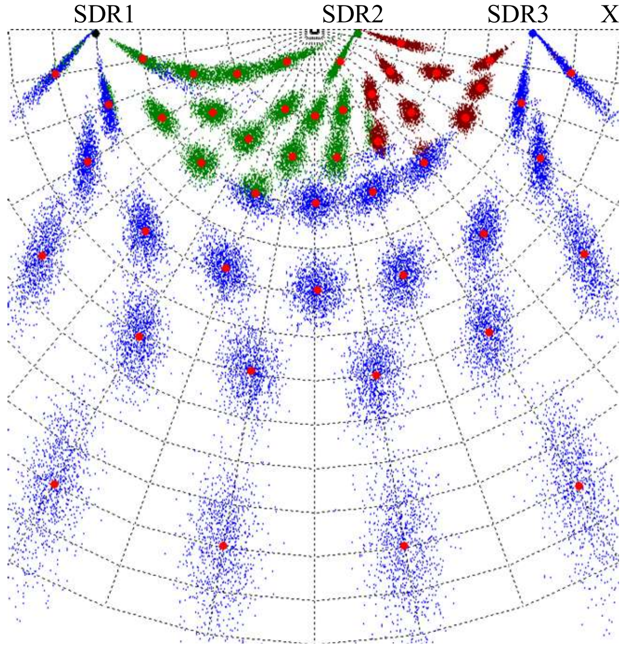

Fig. 9. Simulation results of determining the coordinates of an unmanned aerial vehicle for the case of using the first SDR receiver and the second SDR receiver; the second SDR receiver and the third SDR receiver; the first SDR receiver and the third SDR receiver with the selection of the optimal pair

The results shown in Fig. 9 are similar to the pattern depicted in Fig. 8. The only difference is that when choosing the optimal pair, another pair (second SDR receiver, third SDR receiver) is considered (brown marks).

From the analysis of Fig. 9, one can see that when finding an unmanned aerial vehicle between two SDR receivers, information from them is used up to a certain distance. This corresponds to the theoretically obtained results. In other words, the pair of SDR receivers is selected for which the distance from the unmanned aerial vehicle to the normal from the center of the base is minimal.

For the pair (first SDR receiver – third SDR receiver), the angles of intersection of the bearings are sharper, which leads to larger errors in determining the coordinates. In some cases, false switching of pairs of SDR receivers is noticeable. This is due to the fact that for both cases the angles of intersection of the bearings are close in value and due to errors in determining the bearings there is a certain randomness.

The pair (first SDR receiver – third SDR receiver) has the largest base of the considered options, that is, starting from a certain range, the angle of intersection of the bearings for this case is closest to 90°, the area of the ellipses of scattering of coordinate measurement errors is minimal, which determines its choice.

Thus, the results of simulation modeling allowed us to assess the accuracy of the direction finding of an unmanned aerial vehicle and determine the main factors influencing the formation of true and false points of intersection of the bearings.

6. Discussion of results related to improving a method for determining the coordinates of an unmanned aerial vehicle

A network of three SDR receivers located on the same line was considered (Fig. 1). To select a pair of SDR receivers, it was taken into account that the ellipse of scattering errors in determining coordinates has a minimum area when the unmanned aerial vehicle is located at a point where the angle of intersection of the bearings is close to 90°. The selection of a pair of SDR receivers ensured the most accurate determining the coordinates of the unmanned aerial vehicle and the selection (reduction) of false bearings.

The method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when used in pairs has been improved, which, unlike the known ones (for example, [7, 19, 20]), provides for the following:

– measuring bearings by each SDR receiver;

– determining pairwise angles of intersection of bearings;

– determining the maximum of pairwise angles of intersection;

– determining a pair of SDR receivers for further calculations;

– using the triangulation method to determine the coordinates of the unmanned aerial vehicle.

The accuracy of determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when used in pairs has been assessed. The assessment was carried out by mathematical modeling. The Monte Carlo statistical test method was used.

The results of modeling the determination of coordinates of an unmanned aerial vehicle for the case of using different pairs of SDR receivers are shown in Fig. 5–7. From the analysis of Fig. 5–7 it is clear that the shape, orientation, and size of the error ellipses depend on the relative location in space of the SDR receivers and the unmanned aerial vehicle.

Fig. 8, 9 show the results of modeling when using SDR receivers in pairs with the selection of the optimal pair of SDR receivers. The analysis of Fig. 8 reveals a reduction in the size of the scattering ellipses (errors in measuring the coordinates of an unmanned aerial vehicle) by (20–40) % due to the use of information from the optimal pair for calculating the coordinates. In the area opposite the third SDR receiver and to the left of it, false positives are observed due to the fact that the angles of intersection of the bearings are close to acute. From the analysis of Fig. 8 it is seen that when finding an unmanned aerial vehicle between the first SDR receiver and the second SDR receiver, information from them is used up to a certain distance, which corresponds to the theoretically obtained results. For the pair (first SDR receiver – third SDR receiver), the angles of intersection of the bearings are more acute, which leads to larger errors in determining the coordinates.

From the analysis of Fig. 9 it is seen that when finding an unmanned aerial vehicle between two SDR receivers, up to a certain distance, information from them is used, which corresponds to the theoretically obtained results. In other words, the pair of SDR receivers is selected for which the distance from the unmanned aerial vehicle to the normal from the center of the base is minimal. For the pair (first SDR receiver – third SDR receiver), the angles of intersection of the bearings are sharper, which leads to greater errors in determining the coordinates. In some cases, false switching of pairs of SDR receivers is noticeable. This is due to the fact that for both cases the angles of intersection of the bearings are close in value and due to errors in determining the bearings there is a certain randomness.

The pair (first SDR receiver – third SDR receiver) has the largest base of the considered options. Starting from a certain distance, the angle of intersection of the bearings for this case is closest to 90°. The area of the ellipses of the scattering errors of coordinate measurement is minimal, which determines its choice.

The limitations of our method are:

– it is used only for measuring the coordinates of unmanned aerial vehicles;

– a network of three SDR receivers located in a line is considered;

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

The disadvantage of the method is the use of the SDR receivers in a line, which limits its application to certain cases.

Further research is aimed at investigating the possibility of determining the coordinates of an unmanned aerial vehicle with a different configuration of the SDR receiver network.

7. Conclusions

1. The main stages of a method for determining the coordinates of an unmanned aerial vehicle by a network of three SDR receivers when they are used in pairs:

– measuring bearings by each SDR receiver;

– determining the pairwise angles of intersection of bearings;

– determining the maximum of the pairwise angles of intersection;

– determining a pair of SDR receivers for further calculations;

– using the triangulation method for determining the coordinates of an unmanned aerial vehicle.

2. The accuracy of determining the coordinates of an unmanned aerial vehicle by a network of three SDR re-

ceivers when used in pairs has been assessed. It was found that:

– the shape, orientation, and size of the error ellipses depend on the relative location in space of the SDR receivers and the unmanned aerial vehicle;

– the size of the scattering ellipses (errors in measuring the coordinates of the unmanned aerial vehicle) is reduced by (20–40) % due to the use of information from the optimal pair for calculating the coordinates;

– in some cases, false switching of pairs of SDR receivers is noticeable. This is due to the fact that for both cases the angles of intersection of the bearings are close in value and due to errors in determining the bearings there is a certain randomness;

– the pair (first SDR receiver – third SDR receiver) has the largest base of the considered options. Starting from a certain range, the angle of intersection of the bearings for this case is closest to 90°. The area of the ellipses of scattering errors of coordinate measurement is minimal, which determines its choice;

– when moving an unmanned aerial vehicle beyond the network coverage area of a pair of SDR receivers, it is advisable to use another pair; this involves the use of a "chain" of SDR receivers.

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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