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IMPROVING A METHOD FOR DETERMINING THE COORDINATES OF A RECONNAISSANCE UNMANNED AERIAL VEHICLE BY A SMALL-BASED NETWORK OF TWO SOFTWARE-DEFINED RADIO RECEIVERS

This study investigates the process for determining the coordinates of a reconnaissance unmanned aerial vehicle. The task addressed relates to determining the coordinates of a reconnaissance unmanned aerial vehicle using a small-scale network of mobile passive location devices.

A method for determining the coordinates of a reconnaissance unmanned aerial vehicle has been improved, which, unlike known ones, involves:

– determining bearings for a reconnaissance unmanned aerial vehicle;

– using the triangulation method.

The accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-scale network of two Software-Defined Radio receivers has been assessed. It has been established that the shape and orientation of the error ellipses depends on the position of the reconnaissance unmanned aerial vehicle relative to the Software-Defined Radio receivers. The accuracy of determining the coordinates significantly deteriorates in cases where the polar angle of observation from the center of the base approaches 0° or 180°. The highest accuracy of determining coordinates is achieved when the reconnaissance unmanned aerial vehicle is located on the traverse to the middle of the base.

It has been established that for small bases there is a more pronounced unevenness of the dependence of accuracy on the position of the reconnaissance unmanned aerial vehicle compared to larger bases. At long ranges, errors for small bases increase sharply. It has been established that with a decrease in the base length, the area of the error ellipses increases, which indicates a deterioration in the potential accuracy characteristics of the system and an increase in the average circular error. At the same time, the geometric features are preserved, the orientation of the ellipses and the nature of their location relative to the base line remain constant

Keywords: unmanned aerial vehicle, small-base network, Software-Defined Radio receiver, bearing

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1. Introduction

Under current conditions, reconnaissance unmanned aerial vehicles are used to solve various tasks. There is no doubt that the top priority is the acquisition of intelligence information for its further use [1, 2]. It is known [3] that the detection and determination of the coordinates of reconnaissance unmanned aerial vehicles for modern radars is an atypical task. First of all, this is due to the peculiarities of the tactics of application, and the technical characteristics of reconnaissance unmanned aerial vehicles. For example, the relatively low speeds of reconnaissance unmanned aerial vehicles lead to the rejection of signals reflected from them [4]. In addition, under the conditions of operation of modern radars, they become targets for destruction because of their radiation [5].

Therefore, it is advisable to use the principles of passive radar to detect reconnaissance unmanned aerial vehicles. Such detection is possible, which has been proven in well-known works. For example, in [6], mobile portable spectrum analyzers were used. In [7], the use of mobile portable Software-Defined Radio (SDR) receivers is proposed.

The main disadvantage of using mobile portable devices, which are proposed in [6, 7], is the large size of the base (distance between network elements). At such a distance, it is usually difficult to enable the synchronization of network elements, carry out measurement identification, etc.

Therefore, it is advisable to consider the possibility of determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-base network of mobile portable devices. In this case, a method for determining the coordinates of a reconnaissance unmanned aerial vehicle in such a network should be simple [8].

Thus, devising a method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-base network of mobile portable devices is an urgent task.

2. Literature review and problem statement

In [9], to increase the accuracy of determining the coordinates of an air object, the use of a multi-position network, the elements of which are radars, is proposed. It is shown that the operation of radars under an active mode is a prerequisite. The disadvantages of [9] are the inability to ensure the secrecy of the system and the increase in its cost. The reason is the active mode of operation of radars. One of the options for overcoming it is to change the frequency of the radar transmitter. This approach is considered in [10].

In [10], to increase the accuracy of determining the coordinates of an air object, a change in the frequency of the radar transmitter is proposed. The method from [10] provides increased secrecy of the radar operation, compared to [9]. At the same time, the accuracy of determining the coordinates of an air object is low. This is due to the low signal-to-noise ratio at the input of the radar receiving device. In addition, the characteristics and type of radars are not considered.

In [11], to increase the accuracy of determining the coordinates of an air object, the use of a multi-position network is proposed, the elements of which are two-coordinate radars. In this case, such radars have a low accuracy of a single measurement and operate under an active mode. The disadvantages of [11] are the inability to ensure the secrecy of the system, an increase in its cost and ensuring synchronous operation of the elements. This is due to the low value of the signal-to-noise ratio at the input of the receiving device of each of the two-coordinate radars. An option for increasing the signal-to-noise ratio at the input of the receiving device is to use an additional source of information. This approach is considered in [12].

In [12], to improve the accuracy of determining the coordinates of an air object, the additional use of cellular communication is proposed. In this case, coherent addition of signals reflected from the air object is proposed at the expense of the radar and cellular communication stations. The disadvantages of [12] are the inability to ensure the secrecy of the system, its increased cost, and the synchronous operation of the radar and cellular stations. The option of increasing the signal-to-noise ratio at the input of the receiving device is also considered in [13].

In [13], to increase the accuracy of determining the coordinates of an air object, additional use of navigation systems is proposed. In this case, coherent addition of signals reflected from the air object is proposed at the expense of radar and space navigation systems. The disadvantages of [13] are the impossibility of ensuring the secrecy of the system, increasing its cost and ensuring the synchronous operation of the radar and space navigation system.

In [14], to improve the accuracy of determining the coordinates of an air object, additional consideration of the features of its flight path is proposed. In this case, the use of extrapolated coordinates of the air object is proposed when processing radar information. The disadvantages of [14] are the presence of systematic and random extrapolation errors and the accumulation of these errors over time. To reduce these errors, it is advisable to use coherent processing of radar information. This is the approach proposed in [15].

In [15], to enhance the accuracy of determining the coordinates of an air object, the use of an additional source of information is suggested. In this case, coherent addition of signals reflected from an air object is proposed, due to the radar and an additional source of information. The disadvantages of [15] are the reduction of the detection zone of the system and ensuring the synchronous operation of the radar and an additional source of information. The direction for overcoming the difficulties associated with reducing the detection zone of a multi-position system is the use of a multilateration system. This approach is proposed in [16].

In work [16], the use of a multilateration system is proposed to increase the accuracy of determining the coordinates of an air object. In this case, coherent addition of signals reflected from an air object is proposed, due to the radar and the multilateration system. The disadvantages of [16] are the reduction of ensuring the synchronous operation of the radar and the multilateration system.

In [17], the change of radar parameters (transmitting and receiving channels) is proposed to increase the accuracy of determining the coordinates of an air object. In this case, a mandatory condition is the unification of radars into a network. The disadvantages of [17] are the reduced technical complexity of changing radar parameters and ensuring their synchronous operation. To enable synchronous operation of the system, it is advisable to use Multiple Input – Multiple Output (MIMO) networks. This is the approach proposed in [18].

In [18], the use of a MIMO radar network was proposed to increase the accuracy of determining the coordinates of an air object. The disadvantages of [18] are the impossibility of ensuring the secrecy of the system, the incoherence of the network operation, and the increase in its cost. To ensure coherent information processing, it is advisable to take into account the features of the flight trajectory of air objects. This approach is considered in [19].

In [19], the features of the formation and flight of a group of unmanned aerial vehicles were considered. It was noted that the detection and determination of the coordinates of a group of unmanned aerial vehicles significantly affects the accuracy of determining the coordinates of each unmanned aerial vehicle. The disadvantages of [19] are the impossibility of ensuring the secrecy of the system and the low accuracy of determining the coordinates of the unmanned aerial vehicle.

Thus, known methods for increasing the accuracy of determining the coordinates of an air object [9–19] have a number of disadvantages. The main ones are:

– the impossibility of ensuring the secrecy of the system;

– increase in the cost and complexity of building the system;

– low accuracy of determining the coordinates of an air object;

– enabling the synchronous operation of the radar and various additional systems.

To avoid the above-mentioned disadvantages of known methods for increasing accuracy, it is advisable to use portable mobile passive location devices (for example, SDR receivers). In this case, it is appropriate to investigate the issue of choosing a base between such mobile portable SDR receivers. Therefore, the possibility of determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-base network of mobile passive location devices remains a task to be tackled.

3. The aim and objectives of the study

The purpose of our research is to devise a method for determining the coordinates of a reconnaissance unmanned aerial vehicle using a small-scale network of two SDR receivers. This will make it possible to increase the accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle.

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 a reconnaissance unmanned aerial vehicle using a small-scale network of two SDR receivers;

– to assess the accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle using a small-scale network of two SDR receivers.

4. The study materials and methods

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

The principal hypothesis of the study assumes that the use of two SDR receivers by a small-scale network could increase the accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle. This is especially important when determining the coordinates of a reconnaissance unmanned aerial vehicle.

The following assumptions and simplifications were adopted during the study:

– the number of SDR receivers in a small-scale network is two;

– a method for determining coordinates in a small-scale network is triangulation;

– there are no passive and active interferences during measurements;

– unhindered reception of signals by each SDR receiver of the small-scale network is ensured;

– two SDR receivers are located on the same line;

– two SDR receivers of the small-scale network are synchronized;

– the Monte Carlo method (statistical tests) is used;

– the simulation was carried out using the example of the reconnaissance unmanned aerial vehicle "Orlan-10" (Russian Federation);

– the length of the base B between SDR1 and SDR2 is assumed to be 1000 m, 500 m, which corresponds to the values of small bases [20, 21];

– the distance from the center of the base to the reconnaissance unmanned aerial vehicle did not exceed 7 km;

– SDR1 and SDR2 receivers use identical antenna systems;

– Gaussian law of distribution of errors in determining the coordinates of the reconnaissance unmanned aerial vehicle by SDR1 and SDR2 receivers;

– software – multifunctional integrated environment C++ Builder;

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

The following research methods were used in our study:

– passive radar methods;

– multi-position radar methods;

– mathematical apparatus of matrix theory;

– methods of probability theory and mathematical statistics;

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

– methods of system analysis;

– methods of digital signal processing theory;

– methods of mathematical modeling.

The research methods were selected based on the formulated research tasks. Thus, when determining the main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-scale network of two SDR receivers, the following theoretical methods were used:

– passive radar methods;

– multi-position radar methods;

– mathematical apparatus of matrix theory;

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

– methods of digital signal processing theory.

When assessing the accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-scale network of two SDR receivers, the following theoretical methods were applied:

– methods of probability theory and mathematical statistics;

– methods of system analysis.

When modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle, experimental methods of mathematical modeling were used. The Monte Carlo method was chosen as the principal method. The main advantages of the Monte Carlo method are versatility, the ability to work under conditions of uncertainty, and ease of implementation. The statistical accuracy of the method is due to the use of a large amount of input data when modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle (1000 measurements were carried out for each point).

5. Results of investigating a method for determining the coordinates of a reconnaissance unmanned aerial vehicle

5. 1. Main stages in determining the coordinates of a reconnaissance unmanned aerial vehicle

A small-scale network of two SDR receivers is shown in Fig. 1.

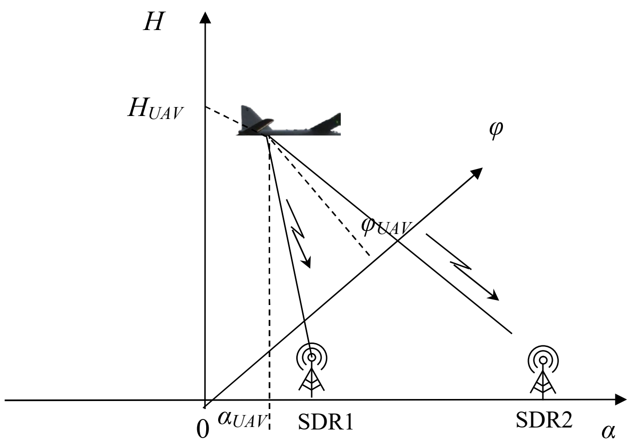

Fig. 1. Network of three SDR receivers located on the same line

A signal from the reconnaissance unmanned aerial vehicle is received by two SDR1 and SDR2, which are elements of a small-base network. The onboard systems of the reconnaissance unmanned aerial vehicle are signal sources for the elements of the small-base network [4]. The elements of the small-base network measure the coordinates of the reconnaissance unmanned aerial vehicle. Fig. 1 shows:

– α_{UAV} – the first coordinate of the reconnaissance unmanned aerial vehicle;

– D_{UAV} – the second coordinate of the reconnaissance unmanned aerial vehicle;

– H_{UAV} – the third coordinate (for example, height) of the reconnaissance unmanned aerial vehicle.

When determining main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-base network of two SDR receivers, the case of two coordinates (α_{UAV}, φ_{UAV}) was considered (Fig. 2). In Fig. 2, the base between SDR1 and SDR2 is marked as B.

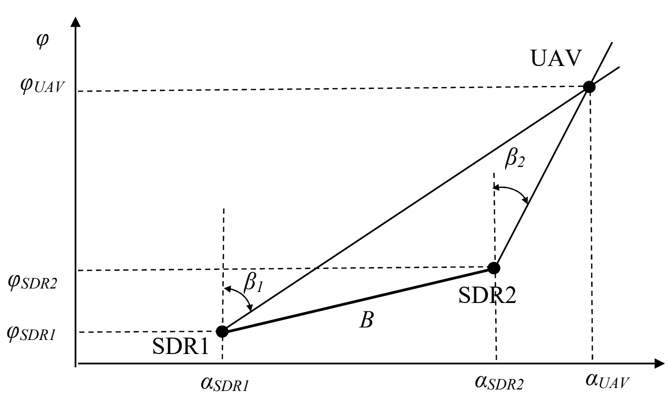

Fig. 2. Determining the coordinates of a reconnaissance unmanned aerial vehicle in the coordinate system (α, φ)

The main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle using a small-scale network of two SDR receivers are shown in Fig. 3:

1. Input of initial data: coordinates of SDR receivers α_{SDR1}, φ_{SDR1}, α_{SDR2}, φ_{SDR2}, value of base B.
2. Determining the bearings to reconnaissance unmanned aerial vehicle SDR1 by receiver (β_1) and SDR2 by receiver (β_2).
3. Determining the first coordinate of reconnaissance unmanned aerial vehicle α_{UAV} from expression (1)

$$\alpha_{UAV} = \frac{\alpha_{SDR2}\sin\beta_2 - \varphi_{SDR2}\cos\beta_2}{\sin(\beta_2 - \beta_1)}\cos\beta_1. \quad (1)$$

4. Determining the second coordinate of the reconnaissance unmanned aerial vehicle φ_{UAV} from expression (2)

$$\varphi_{UAV} = \frac{\alpha_{SDR2}\sin\beta_2 - \varphi_{SDR2}\cos\beta_2}{\sin(\beta_2 - \beta_1)}\sin\beta_1. \quad (2)$$

5. Determining the range to the reconnaissance unmanned aerial vehicle D_{UAV} using expression (3)

$$D_{UAV} = \frac{\alpha_{SDR2}\sin\beta_2 - \varphi_{SDR2}\cos\beta_2}{\sin(\beta_2 - \beta_1)}. \quad (3)$$

6. Checking the location of the reconnaissance unmanned aerial vehicle in the coverage area of SDR1 and SDR2 receivers.
7. When the reconnaissance unmanned aerial vehicle is found in the coverage area of SDR1and SDR2 receivers, the coordinates of the reconnaissance unmanned aerial vehicle are updated.
8. If condition 7 is not met, the flight trajectory of the reconnaissance unmanned aerial vehicle is determined.

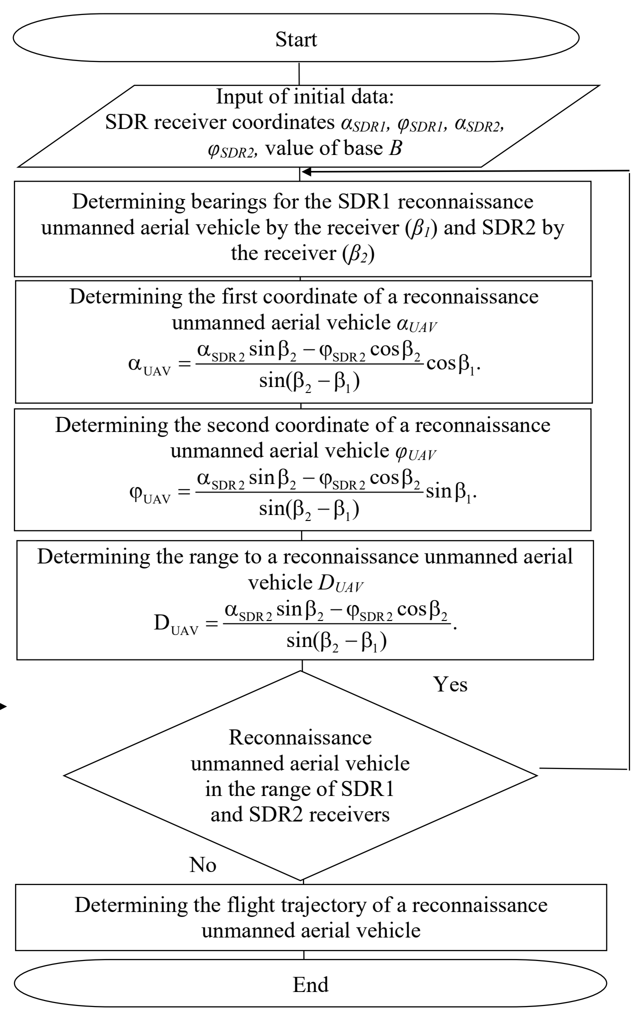

Fig. 3. Main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle using a small-scale network of two SDR receivers

5. 2. Assessing the accuracy in determining the coordinates of a reconnaissance unmanned aerial vehicle

To assess the accuracy of determining the coordinates of a reconnaissance unmanned aerial vehicle, mathematical modeling was performed using the methodology from [20, 21].

Fig. 4 shows the results of modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle with a base value of $B = 1000$ m. There is no systematic error component. The bearing measurement error for both SDR receivers is considered the same and is described by a normal distribution law with zero mathematical expectation and a standard deviation of 2.5°. Such conditions correspond to the use of weakly directional antennas in the maximum method under the condition that the signal arrives from a relatively short distance, which provides a high signal-to-noise ratio at the receiving point.

Fig. 5 shows the results of modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle with a base value of $B = 1000$ m, with improved characteristics of direction finding accuracy. The root mean square error of a single measurement is taken to be 1.0°, which allows us to assess its impact on the final results of determining the coordinates.

The red dots in Fig. 4, 5 indicate the true position of the reconnaissance unmanned aerial vehicle. The green dots indicate the results of determining the coordinates of the reconnaissance unmanned aerial vehicle. 1000 measurements were performed for each point, which allowed us to estimate the configuration of the scattering ellipses and determine the average circular error in determining the coordinates with reasonable practical accuracy.

Analysis of Fig. 4, 5 reveals that the shape and orientation of the error ellipses depends on the position of the reconnaissance unmanned aerial vehicle relative to SDR1 and SDR2. It was found that the accuracy of determining the coordinates significantly deteriorates in cases where the polar angle of observation from the center of the base approaches 0° or 180°. Under such conditions, even minor errors in direction finding lead to significant linear deviations at the intersection point of the direction finding lines and, accordingly, to significant errors in determining the coordinates of the reconnaissance unmanned aerial vehicle. The highest accuracy of determining the coordinates of the reconnaissance unmanned aerial vehicle is achieved when the reconnaissance unmanned aerial vehicle is on the traverse to the middle of the base. In this case, the observation angle is 90°, and the distance to the middle of the base is proportional to the length of the base. This is due to the fact that the angle of intersection of the bearings is optimal. This is what minimizes the average measurement error.

Studies have also shown that for small bases there is a more pronounced unevenness in the dependence of accuracy on the position of the reconnaissance unmanned aerial vehicle compared to larger bases. At long ranges, the errors for small bases increase sharply, which is due to a decrease in the angle of intersection of the bearings and, as a result, a decrease in the geometric accuracy of the triangulation method.

Fig. 6 shows the results of modeling the determination of the coordinates of the reconnaissance unmanned aerial vehicle with a base size of $B = 500$ m. The root-mean-square error of a single measurement is taken to be 2.5°.

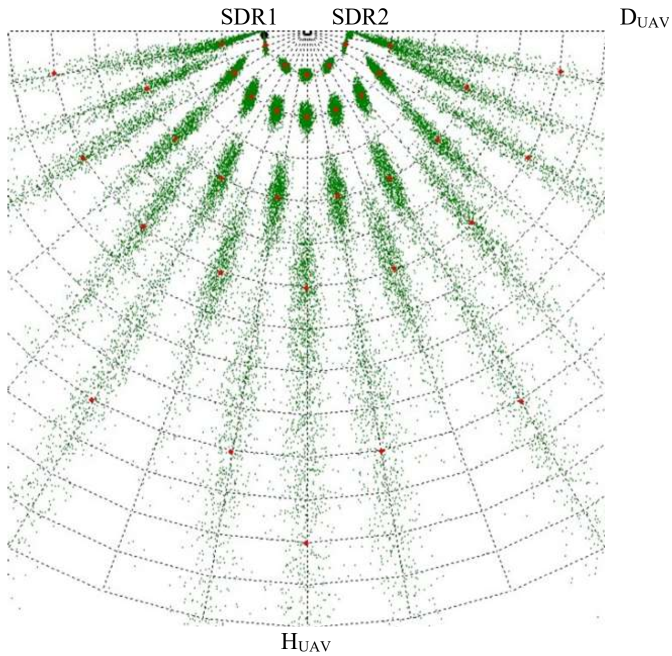

Fig. 4. Results from simulating the determination of coordinates of a reconnaissance unmanned aerial vehicle at $B = 1000$ m, single measurement accuracy $\sigma = 2.5°$

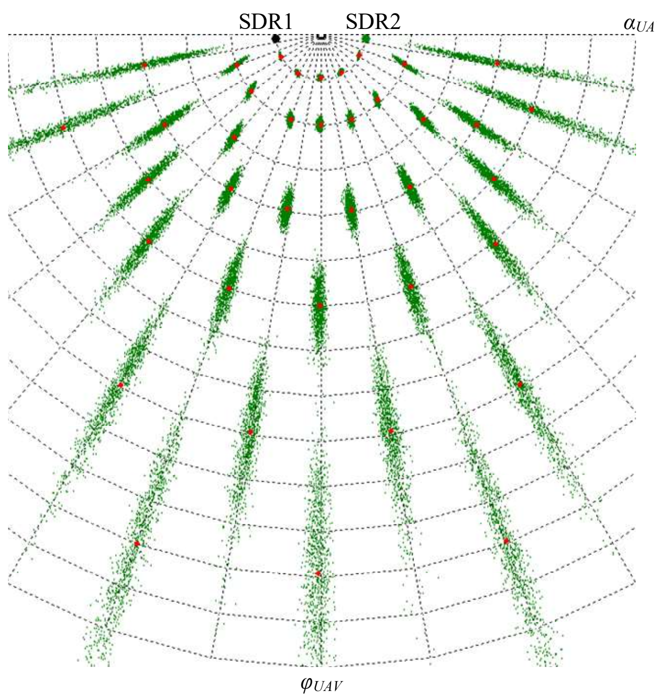

Fig. 5. Simulation results from determining the coordinates of a reconnaissance unmanned aerial vehicle at $B = 1000$ m, single measurement accuracy $\sigma = 1.0°$

Fig. 7 shows the results of modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle with a base value of $B = 500$ m. The root mean square error of a single measurement is taken to be 2.5°.

Our results reflect the influence of the length of the direction-finding base B on the accuracy of determining coordinates by the triangulation method. Analysis of Fig. 4–7 reveals that with a decrease in the length of the base, the area of the error ellipses increases, which indicates a deterioration in the potential accuracy characteristics of the system and an increase in the average circular error. At the same time, the geometric features are preserved, the orientation of the ellipses and the nature of their location relative to the base line remain constant.

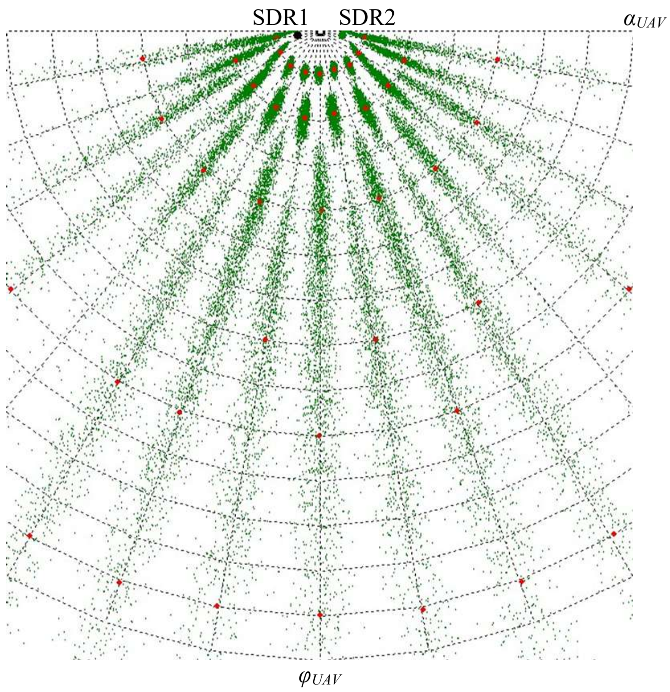

Fig. 6. Simulation results from determining the coordinates of a reconnaissance unmanned aerial vehicle at $B = 500$ m, single measurement accuracy $\sigma = 2.5°$

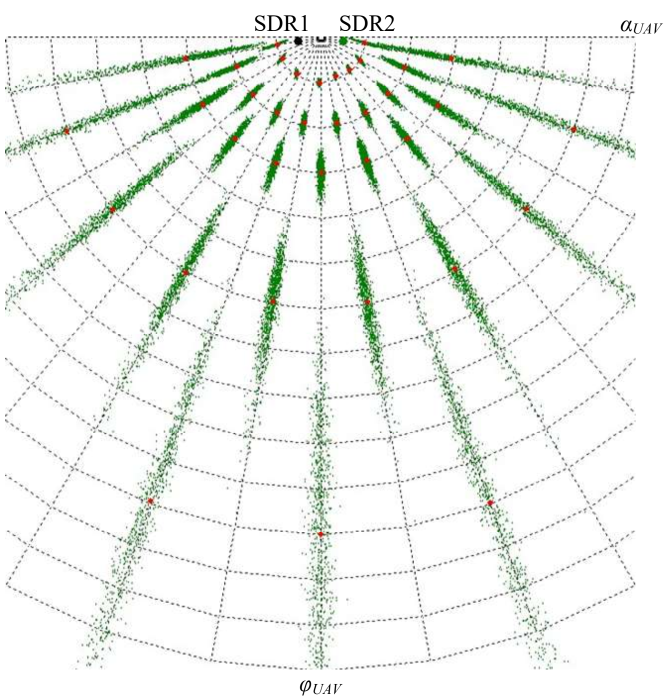

Fig. 7. Simulation results from determining the coordinates of a reconnaissance unmanned aerial vehicle at $B = 500$ m, single measurement accuracy $\sigma = 1.0°$

Thus, the nature of the spatial distribution of errors is invariant to the size of the base, i.e. the shape and direction of the error ellipses remain the same regardless of their value. Changing the length of the direction-finding base inversely affects the scale of the error ellipses. With a decrease in the base, the dimensions of the ellipses increase, which indicates a decrease in the accuracy of determining the coordinates of the reconnaissance unmanned aerial vehicle, and vice versa.

6. Results related to the method for determining coordinates by a small-based network of two SDR receivers: discussion

A small-based network of two SDR receivers was considered (Fig. 1). When determining the main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-based network of two SDR receivers, the case of two coordinates was considered (Fig. 2). The main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-based network of two SDR receivers are shown in Fig. 3. The method for determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-based network of two SDR receivers was improved, which, unlike known ones, provides for the following:

– determination of bearings to a reconnaissance unmanned aerial vehicle;

– use of the triangulation method to determine the coordinates of a reconnaissance unmanned aerial vehicle.

The accuracy in determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-based network of two SDR receivers was assessed. The considered cases correspond to most practical situations of using a small-scale network of two SDR receivers under field conditions.

Analysis of Fig. 4, 5 reveals that the shape and orientation of the error ellipses depend on the position of the reconnaissance unmanned aerial vehicle relative to SDR1 and SDR2. It was found that the accuracy of determining the coordinates significantly deteriorates in cases where the polar angle of observation from the center of the base approaches 0° or 180°. The highest accuracy in determining the coordinates of the reconnaissance unmanned aerial vehicle is achieved when the reconnaissance unmanned aerial vehicle is on the traverse to the middle of the base.

Studies have also shown that for small bases there is a more pronounced unevenness in the dependence of the accuracy on the position of the reconnaissance unmanned aerial vehicle compared to larger bases. At long ranges, the errors for small bases increase sharply, which is due to a decrease in the angle of intersection of the bearings and, as a result, a decrease in the geometric accuracy of the triangulation method.

Fig. 6, 7 show the results of modeling the determination of the coordinates of a reconnaissance unmanned aerial vehicle with a base size of $B = 500$ m. The results reflect the influence of the length of the direction-finding base B on the accuracy of determining the coordinates by the triangulation method.

Analysis of Fig. 4–7 reveals that with a decrease in the base length, the area of the error ellipses increases, which indicates a deterioration in the potential accuracy characteristics of the system and an increase in the average circular error. At the same time, the geometric features are preserved, the orientation of the ellipses and the nature of their location relative to the base line remain constant.

Thus, the nature of the spatial distribution of errors is invariant to the size of the base, i.e., the shape and direction of the error ellipses remain the same regardless of their value. Changing the length of the direction-finding base inversely affects the scale of the error ellipses. With a decrease in the base, the size of the ellipses increases, which indicates a decrease in the accuracy of determining the coordinates of the reconnaissance unmanned aerial vehicle, and vice versa.

The limitations of our method are:

– only SDR receivers are considered as mobile portable devices;

– elements of the small-base network of SDR receivers are arranged in a line;

– heterogeneous interference conditions are not taken into account.

The disadvantage of the method is a decrease in the accuracy of determining the coordinates of the unmanned aerial vehicle when the base B between SDR receivers is reduced.

The area of further research is the use of other portable mobile devices as elements of the small-base network.

7. Conclusions

1. The main stages of the method for determining the coordinates of a reconnaissance unmanned aerial vehicle:

– determining the bearings to the reconnaissance unmanned aerial vehicle by each SDR receiver;

– determining the first coordinate of the reconnaissance unmanned aerial vehicle;

– determining the second coordinate of the reconnaissance unmanned aerial vehicle;

– determining the range to the reconnaissance unmanned aerial vehicle;

– checking the location of the reconnaissance unmanned aerial vehicle in the range of the SDR receivers;

– updating the coordinates of the reconnaissance unmanned aerial vehicle.

2. The accuracy in determining the coordinates of a reconnaissance unmanned aerial vehicle by a small-base network of two SDR receivers has been assessed. It was found that:

– the shape and orientation of the error ellipses depend on the position of the reconnaissance unmanned aerial vehicle relative to the SDR receivers;

– the accuracy in determining the coordinates significantly deteriorates in cases where the polar angle of observation from the center of the base approaches 0° or 180°;

– the highest accuracy in determining the coordinates is achieved when the reconnaissance unmanned aerial vehicle is on the traverse to the middle of the base;

– for small bases, there is a more pronounced unevenness in the dependence of the accuracy on the position of the reconnaissance unmanned aerial vehicle compared to larger bases;

– at long ranges, the errors for small bases increase sharply;

– with a decrease in the base length, the area of the error ellipses increases, which indicates a deterioration in the potential accuracy characteristics of the system and an increase in the average circular error. At the same time, the geometric features are preserved, the orientation of the ellipses and the nature of their location relative to the base line remain constant.

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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