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DEVISING A METHOD FOR DETERMINING THE COORDINATES OF AN UNMANNED AERIAL VECHICLE VIA A NETWORK OF PORTABLE SPECTRUM ANALYZERS

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The object of this study is the process of determining the coordinates of unmanned aerial vehicles. The study hypothesis assumed that the use of a network of portable spectrum analyzers could make it possible to detect the signals of the on-board systems of an unmanned aerial vehicle and reduce the mean square error in determining its coordinates.

A method for determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers has been improved, which, unlike known ones, allows for the following:

– using signals of on-board equipment of an unmanned aerial vehicle;

– using a network of portable spectrum analyzers;

– application of both the triangulation and the difference-ranging method for determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers;

– carrying out spectral analysis of the signals of the on-board systems of the unmanned aerial vehicle (carried out additionally if necessary).

Experimental studies have shown the capabilities of a portable spectrum analyzer to receive signals and display their spectra and spectrograms.

The accuracy in determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers was evaluated. It has been established:

– the use of a network of portable spectrum analyzers significantly reduces the root mean square error in measuring the coordinates of an unmanned aerial vehicle by approximately 50 % compared to the error of one portable spectrum analyzer;

– as the distance from the network elements of portable spectrum analyzers increases, the mean square error increases.

– the use of a network of portable spectrum analyzers reduces the root mean square error in determining the coordinates of an unmanned aerial vehicle by an average of 2.29–2.62 times compared to the radar P-19MA, depending on the range

Keywords: unmanned aerial vehicle, network of portable spectrum analyzers, differential remote sensing method

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1. Introduction

Under today's conditions, the scope of use of unmanned aerial vehicles is constantly expanding, including threats to people and equipment. This expansion of the application of unmanned aerial vehicles primarily concerns the military [1]. It is known that radars are the main means for detecting unmanned aerial vehicles [2, 3]. However, because of the small value of the effective scattering surface, the detection of unmanned aerial vehicles by radars is significantly complicated. A low effective scattering surface, in turn, leads to a low signal-to-noise ratio. It also significantly affects the accuracy of determining the coordinates of unmanned aerial vehicles by existing radars. In addition, the accuracy in determining the coordinates of unmanned aerial vehicles does not meet the requirements for solving the task of secondary and tertiary processing of radar information [4].

Increasing the signal-to-noise ratio to increase the accuracy of determining the coordinates of unmanned aerial vehicles by known methods requires an increase in the energy potential of the radar. Also, increasing the accuracy in determining the coordinates of unmanned aerial vehicles requires an increase in the number of radars. These methods are extensive and require a significant increase in the cost of the system.

In wartime, radars using active location techniques are potential targets for destruction. This becomes possible because of the possible detection of radar radiation by means of radio and electronic reconnaissance of the enemy [5].

Given the above, means and systems for passive location are actively developing – radio, acoustic, etc. The advantages of such systems are the value of the signal-to-noise ratio exceeding that in radars and, of course, ensuring the stealth of operation. Stealth of work, in turn, is associated with ensuring high survivability of such passive systems.

Therefore, it is a relevant task to devise a method for increasing the accuracy in determining the coordinates of unmanned aerial vehicles in passive location systems.

2. Literature review and problem statement

In [6], increasing the accuracy of determining the coordinates of aerial objects is achieved by reducing the distance between radars. This leads to an increase in the signal-to-noise ratio. The proposed compaction of radars leads to an increase in the cost of the radar system, a decrease in the stealth of operation, etc. Issues of ensuring the viability of such a system also remain unresolved.

In [7], a change in the frequency of the probing signal during radar operation is proposed. Such a change in frequency increases the stealth of conducting radio reconnaissance of such a radar. Changing the frequency has no effect on the value of the signal-to-noise ratio. Therefore, the issue of increasing accuracy in the reported method remained unresolved.

In [8], changing the signal type from simple to complex is proposed. The complexity of algorithms for processing such complex signals is expected. The use of complex signals will not significantly affect the accuracy of determining the coordinates of unmanned aerial vehicles. Therefore, this issue remained unresolved.

In [9], it is also suggested that the accuracy of determining the coordinates of aerial objects can be increased by reducing the distance between radars. But, unlike [6], the radars are connected in a network. Increasing the number of radars and combining them into a network leads to an increase in the signal-to-noise ratio. The proposed compaction of radars leads to an increase in the cost of the radar system, a decrease in the stealth of operation, etc. Also in [9] the combination of two-coordinate radars into a network is considered, which is problematic. Issues of ensuring the viability of such a system remain unresolved.

In [10], the creation of a network of two radars and the use of coherent signal processing is proposed. The issue of ensuring synchronicity in the operation of radars and compatible processing of radar information remains unresolved.

In [11], it is proposed to increase the accuracy of determining the coordinates of an aerial object with an increase in the signal/noise ratio by adding the energy potential of the signals of cellular communication stations. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [12], it is proposed to increase the accuracy of determining the coordinates of an aerial object in the system of two surveillance radars and to increase the signal/noise ratio due to the energy potential of signals from cellular communication stations. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [13], it is proposed to increase the accuracy of determining the coordinates of an aerial object while increasing the signal/noise ratio by adding the energy potential of the signals of navigation signals of space systems. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [14], it is proposed to increase the accuracy of determining the coordinates of an aerial object while increasing the signal/noise ratio by adding the energy potential of signals of an additional reception channel. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [15], a model of the system [14] and its detection zone are proposed. It has been established that the size of the detection zone of such a system decreases, which significantly affects the spatial capabilities of detecting aerial objects. The issue of improving the accuracy of determining the coordinates of aerial objects also remains unresolved.

In [16], it is proposed to increase the accuracy of determining the coordinates of the object while increasing the signal/noise ratio by adding the energy potential of the multilateration system. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [17], it is proposed to increase the accuracy of determining the coordinates of an aerial object due to the complication of radar information processing algorithms. At the same time, the maximum plausible estimate of the coordinates of the aerial object was used. The issue of increasing accuracy when using the most plausible estimate of the coordinates of an aerial object remains unresolved.

In [18], a simplification of the algorithms from [17] was proposed through the use of the most likely estimates of the coordinates of the aerial object with a quadratic objective function. The use of only such functions leads to significant errors in determining the coordinates of an aerial object. The issue of increasing the accuracy when using the most likely quadratic objective function for estimating the coordinates of an aerial object remains unresolved.

In [19], it is proposed to increase the accuracy of determining the coordinates of an aerial object by radar while increasing the signal/noise ratio by adding the energy potential of signals of the multilateration system. The issue of ensuring the synchronization of the system's operation and the secrecy of the operation remains unresolved.

In [20], a method for changing the location of radars depending on the possible flight route of an aerial object is proposed. In this case, a genetic algorithm is used. The issue of increasing the accuracy of determining the coordinates of an aerial object in such an adaptive system remains unresolved.

In [21], it is proposed to increase the accuracy of determining the coordinates of an aerial object with an increase in the signal/noise ratio by adding the energy potential of the signals of the sources that receive the sound signal. The issue of synchronizing the work of the components of such a system remains unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [22], it is proposed to increase the accuracy in determining the coordinates of unmanned aerial vehicles Shahed [23] by increasing the signal-to-noise ratio by adding the energy potential of the signals of the sources receiving the sound signal. The issues of synchronizing the work of the components of such a system and its small detection range remain unresolved. This, in turn, does not solve the issue of increasing the accuracy of aerial objects.

In [24], the creation of a network of several radars and the application of control of reception and transmission channels is proposed. The issue of synchronizing the operation of all transmitting and receiving channels of the system and improving the accuracy of determining the coordinates of an aerial object remains unresolved.

In [25] it is also proposed to create a network of several (indeterminate number) radars with a circular view. The issue of synchronizing the operation of all network radars and increasing the accuracy of determining the coordinates of an aerial object remains unresolved.

In [26], a method for detecting an aerial object by an active radar using a passive reception channel is proposed. Such a system provides an increase in the conditional probability of correct detection up to 30 %. The issue of increasing the accuracy of determining the coordinates of an aerial object remained unresolved.

In [27], it is proposed to use a Software Defined Radio (SDR) receiver to increase the accuracy of determining the coordinates of aerial objects. In this case, it is proposed to combine such SDR receivers into the system. At the same time, such a system works separately from the radar and can be used both as a separate system and as a means of preliminary targeting for the radar. The disadvantage of [25] is the mandatory use of specialized software and hardware. The issue of using an omnidirectional antenna remains unresolved, which leads to significant errors in determining the coordinates of aerial objects.

Our review of the literature [6–27] demonstrates that the use of methods and means of passive location is relevant. At the same time, especially under the conditions of hostilities, it is important to ensure the secrecy of the system's operation, the secrecy of the detection of an unmanned aerial vehicle. Also relevant is the portability of devices for detecting unmanned aerial vehicles, conducting an operational express analysis of the presence or absence of unmanned aerial vehicles in the airspace.

Therefore, it is a relevant task to devise a method for determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers.

3. The aim and objectives of the study

The purpose of our study is to increase the accuracy in determining the coordinates of an unmanned aerial vehicle through the use of a network of portable spectrum analyzers. This will make it possible, if necessary, to provide radar targeting and improve the quality of tracking of an unmanned aerial vehicle. It will also increase the survivability of the radar by stealthily operating a network of portable spectrum analyzers.

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

– to outline the main stages of the method for determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers;

– to conduct an experimental study on the possibility of receiving signals with a portable spectrum analyzer;

– to evaluate the accuracy in determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers.

4. The study materials and methods

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

The main hypothesis of the study assumes that the use of a network of portable spectrum analyzers will make it possible to detect the signals of the on-board systems of an unmanned aerial vehicle and reduce the mean square error in determining its coordinates. This will make it possible, if necessary, to provide radar targeting and improve the quality of tracking of an unmanned aerial vehicle. It will also increase the survivability of the radar by stealthily operating a network of portable spectrum analyzers. This is especially important in the context of modern wars and armed conflicts.

The following research methods were used during the research:

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

The following limitations and assumptions were adopted during the research:

– a portable spectrum analyzer considered was Tiny SA Ultra;

– preliminary calibration of the Tine SA Ultra portable spectrum analyzer was carried out;

– the Tiny SA Ultra portable spectrum analyzer is set to work under an Ultra mode;

– an unmanned aerial vehicle is considered as an aerial object;

– when conducting mathematical modeling regarding the assessment of the accuracy in determining the coordinates of an unmanned aerial vehicle, the unmanned aerial vehicle of the tactical level "Zala" (Russian Federation) was considered;

– there are no obstacles to the detection of an unmanned aerial vehicle;

– signal reception by a portable spectrum analyzer from an unmanned aerial vehicle is ensured;

– portable spectrum analyzers in the network work synchronously;

– the Monte Carlo method for statistical tests was used during the modeling to determine the accuracy of coordinates of an unmanned aerial vehicle;

– software – MATLAB software package version R2024a, MMANA-GAL antenna modeling software;

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

5. Research results on 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

When presenting the material, we shall rely on the results reported in [27]. The network of portable spectrum analyzers considered is shown in Fig. 1.

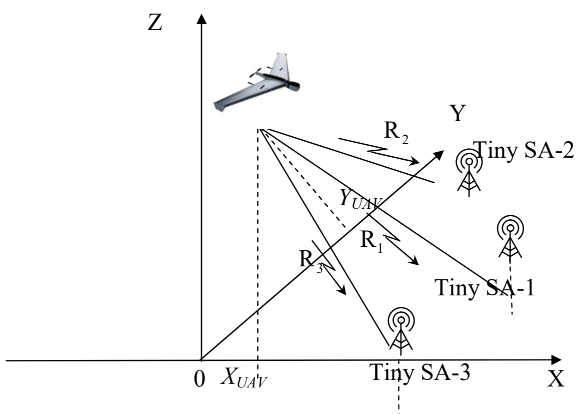

Fig. 1. Tiny SA Ultra network of portable spectrum analyzers

Fig. 1 shows a network of portable spectrum analyzers (Tiny SA-1, Tiny SA-2, Tiny SA-3) designed to measure the coordinates of an unmanned aerial vehicle (unmanned aerial vehicle Zala 421-16 manufactured by the Russian Federation is shown in Fig. 3). The coordinates of the unmanned aerial vehicle were determined in the Cartesian coordinate system (X_{UAV}, Y_{UAV}).

Each portable spectrum analyzer receives signals from the on-board systems of the unmanned aerial vehicle. Such signals can be, for example, signals of a telemetry channel, a channel for issuing target information (a video transmission channel), etc. [28]. It was proved in [27] that the reception of such signals can provide a value of the signal-to-noise ratio higher than the signal-to-noise ratio when detecting an unmanned aerial vehicle by radar. This leads to an increase in the accuracy of determining the coordinates of an unmanned aerial vehicle.

The task of determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers has been formulated. A feature of the structure of a portable spectrum analyzer is the absence of heterogeneous interfaces. This determines the impossibility of directly connecting a portable spectrum analyzer to a computer for the purpose of automated information processing. This fact complicates the structure of a network of portable spectrum analyzers. Therefore, in contrast to [27], the triangulation method [29, 30] was used to determine the coordinates of an unmanned aerial vehicle. The practical implementation of the triangulation method involves either directly plotting the determined bearings on the terrain map and geometric determination of the coordinates of the unmanned aerial vehicle, or it is possible to use specialized mathematical software (for example, "Virazh-planshet" (Ukraine)) to automate the calculation of the coordinates of an unmanned aerial vehicle using the triangulation method.

To determine coordinates of an unmanned aerial vehicle using a network of two portable spectrum analyzers using the triangulation method, let us consider Fig. 2.

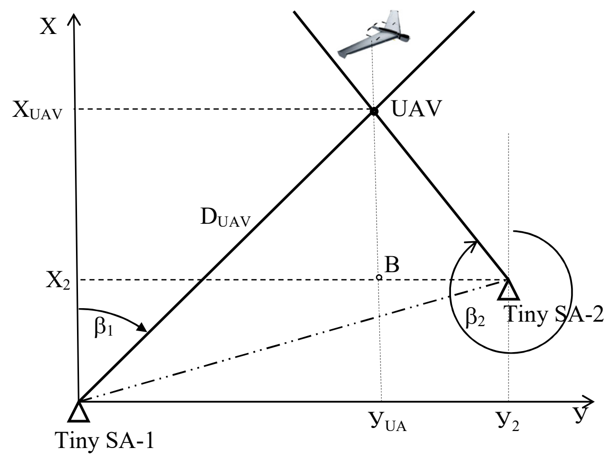

Fig. 2. Determining the coordinates of an unmanned aerial vehicle by a network of two portable spectrum analyzers using the triangulation method

The main stages of the triangulation method for determining the coordinates of an unmanned aerial vehicle using a network of two portable spectrum analyzers are as follows (Fig. 3):

1. Input of initial data: number of portable spectrum analyzers and their type, coordinates of portable spectrum analyzers x_1, y_1, x_2, y_2.

2. Measurements of bearings measured by the first (β_1) and second (β_2) portable spectrum analyzers.

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

$$x_{UAV} = \frac{X_2 \sin\beta_2 - Y_2 \cos\beta_2}{\sin(\beta_2 - \beta_1)} \cos\beta_1. \quad (1)$$

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

$$y_{UAV} = \frac{X_2 \sin\beta_2 - Y_2 \cos\beta_2}{\sin(\beta_2 - \beta_1)} \sin\beta_1. \quad (2)$$

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

$$D_{UAV} = \frac{X_2 \sin\beta_2 - Y_2 \cos\beta_2}{\sin(\beta_2 - \beta_1)}. \quad (3)$$

6. Performing a spectral analysis of the signals of the on-board systems of the unmanned aerial vehicle (additionally carried out as necessary).

7. Checking the fulfillment of the condition regarding the presence of an unmanned aerial vehicle in the range of the spectrum analyzer network.

8. When an unmanned aerial vehicle is found in the range of the spectrum analyzer network, the coordinates of the unmanned aerial vehicle are updated.

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

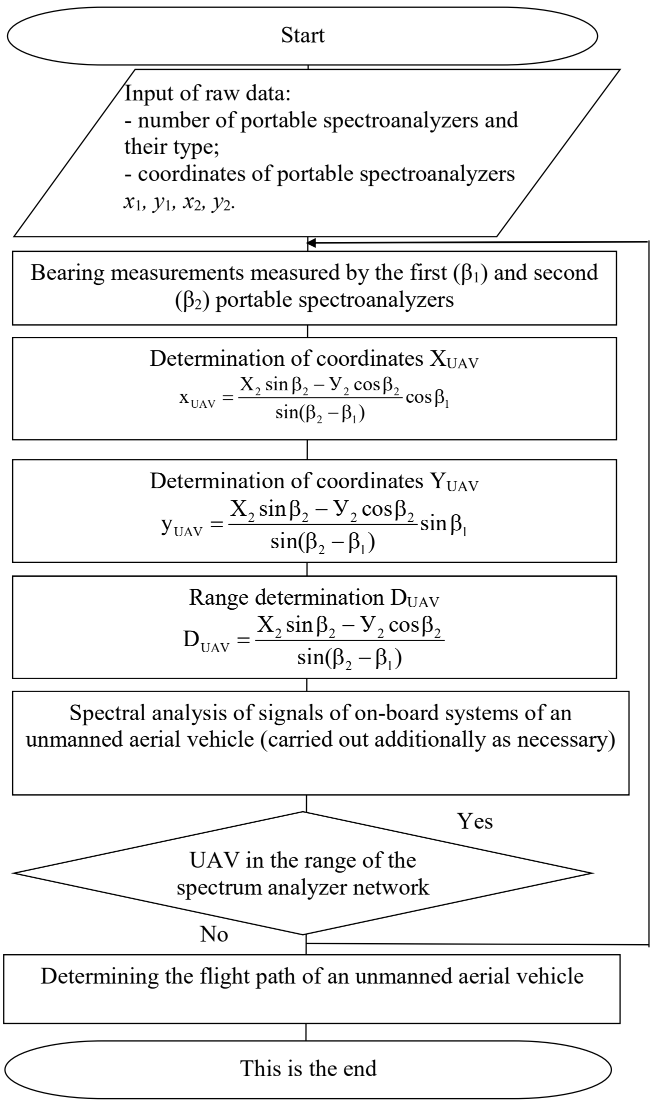

Fig. 3. Main stages of the triangulation method for determining the coordinates of an unmanned aerial vehicle using a network of two portable spectrum analyzers

In the event that it is possible to directly connect portable spectrum analyzers to a computer for the purpose of automated information processing (for example, with the additional use of SDR receivers [27]), a well-known difference-rangefinder method is used to determine the coordinates of an unmanned aerial vehicle by a network of two portable spectrum analyzers [27]. As an SDR receiver, it is advisable to use HackRF One Original (Great Scott Gadgets) [31]. [32] software for HackRF One Original is advisable to employ.

According to the essence of the difference-range measuring method [27], the difference in the time of arrival of the signals of the on-board systems of the unmanned aerial vehicle to each portable spectrum analyzer is measured. We denote this signal difference by $\Delta t_{ij}(X_{UAV}, X_{SAi}, X_{SAj})$, where X_{UAV} is the vector of coordinates of the unmanned aerial vehicle, X_{Sai} is the vector of coordinates of the ith portable spectrum analyzer, X_{Sai} is the vector of coordinates of the jth portable spectrum analyzer. It was assumed that the number of portable spectrum analyzers in the network is three (Fig. 1).

The distance difference from the unmanned aerial vehicle to the portable spectrum analyzer $\Delta R_{ij}(X_{UAV}, X_{SAi}, X_{SAj})$ taking into account the speed of light c is determined from expression (4) [27]:

$$\Delta R_{ij}(X_{UAV}, X_{SAi}, X_{SAj})=c\Delta t_{ij}(\ ). \quad (4)$$

Taking into account the component vectors of the coordinates of the unmanned aerial vehicle $X_{UAV}(x_{UAV}, y_{UAV}, z_{UAV})$ and the components of vectors of the coordinates of portable spectrum analyzers $X_{SAi}(x_{SAi}, y_{SAi}, z_{SAi})$, $X_{SAj}(x_{SAj}, y_{SAj}, z_{SAj})$, we shall rewrite expression (4) in the form of expression (5) :

$$\begin{aligned} &\Delta R_{ij} = R_{SAi} - R_{SAj} = \\ &= \sqrt{\left[\left(x_{SAi} - x_{UAV}\right)^2 + \left(y_{SAj} - y_{UAV}\right)^2 + \left(z_{SAj} - z_{UAV}\right)^2\right]} + \\ &+\Delta R_{SAi} - \\ &-\sqrt{\left[\left(x_{SAj} - x_{UAV}\right)^2 + \left(y_{SAj} - y_{UAV}\right)^2 + \left(z_{SAj} - z_{UAV}\right)^2\right]} - \\ &-\Delta R_{SAj} = c \cdot \Delta t_{ij}. \end{aligned} \quad (5)$$

To simplify expression (5) (in comparison with expression (4)), it is assumed that the first portable spectrum analyzer is considered a reference. The first spectrum analyzer is given an index of zero and is considered zero. All distance differences in the network are calculated relative to the reference portable spectrum analyzer. With this in mind, in expression (5), the distance differences are denoted by the symbol ΔR_i instead of the symbol $\Delta R_{ij}(X_{UAV}, X_{SAi}, X_{SAj})$.

As stated in [27], the system of nonlinear equations (expression (5)) cannot be solved by analytical methods. Therefore, iterative methods are expediently used to solve it. The main stages of the difference-range method for determining the coordinates of an unmanned aerial vehicle using a network of three portable spectrum analyzers are as follows (Fig. 4):

Main stages of the difference-range measuring method for determining the coordinates of an unmanned aerial vehicle using a network of three portable spectrum analyzers:

1. Input of initial data: number of portable spectrum analyzers; coordinates of portable spectrum analyzers x_{SAi}, y_{SAi}, z_{SAi}; a priori values, initial approximations) of the coordinates of the unmanned aerial vehicle $x_{UAV(0)}$, $y_{UAV(0)}$, $z_{UAV(0)}$.

2. Determination of the range to the unmanned aerial vehicle from the ith portable spectrum analyzer from expression (6):

$$\begin{aligned} &R_i = \\ &= \sqrt{\left[\left(x_{SAi} - x_{UAV(0)}\right)^2 + \left(y_{SAi} - y_{UAV(0)}\right)^2 + \left(z_{SAi} - z_{UAV(0)}\right)^2\right]}. \end{aligned} \quad (6)$$

3. At the S-th iteration, expression (7) is used to determine the vector of discrepancies C:

$$C_{SAi(S)}=(R_{SAi(S-1)}-R_{SA(S-1)}-(T_{SAi}-T_{SA}))c;$$

$$i=1, ..., (S-1), \qquad (7)$$

where $R_{SAi(S-1)}$, $R_{SA(S-1)}$ are the distances from the ith and zero portable spectrum analyzers to point $X_{T(0)}$. Point $X_{T(0)}$ has coordinates ($x_{T(0)}$, $y_{T(0)}$, $z_{T(0)}$). Distances $R_{SAi(S-1)}$, and $R_{SA(S-1)}$ are calculated for each (S–1) iteration; the difference ($T_{SAi}-T_{SA}$) is the difference in the reception time of the i-th signals and the zero portable spectrum analyzer.

4. Determining the error matrix (partial derivatives) A_S (expressions (8) to (10)):

$$A_{\text{SAi1(x)}}=\frac{\partial R_{SAi}\left(x_{UAV(S)},y_{UAV(S)},z_{UAV(S)}\right)}{\partial x_{UAV(S)}}, \qquad (8)$$

$$A_{\text{SAi2(x)}}=\frac{\partial R_{SAi}\left(x_{UAV(S)},y_{UAV(S)},z_{UAV(S)}\right)}{\partial y_{UAV(S)}}, \qquad (9)$$

$$A_{\text{SAi3(x)}}=\frac{\partial R_{SAi}\left(x_{UAV(S)},y_{UAV(S)},z_{UAV(S)}\right)}{\partial z_{UAV(S)}}. \qquad (10)$$

5. Determining corrective correction ζ_S (expression (11)):

$$\zeta_S=\left(\left(A_{SA(S-1)}\right)^T R_{SA}A_{SA(S-1)}\right)^{-1}\left(A_{SA(S-1)}\right)^T R_{SA}C. \qquad (11)$$

6. Clarification of the coordinate vector of an unmanned aerial vehicle ($X_S(x_{UAV(S)}, y_{UAV(S)}, z_{UAV(S)})$ from expression (12):

$$X_S(x_{UAV(S)}, y_{UAV(S)}, z_{UAV(S)})=$$
$$=X_S(x_{UAV(S\text{-}1)}, y_{UAV(S\text{-}1)}, z_{UAV(S\text{-}1)})+\zeta_S. \qquad (12)$$

7. Comparison of ζ_S and P values, where P is the minimum permissible value of the corrective correction. When the condition ($\zeta_S<P$) is fulfilled, the calculations are stopped, and it is decided that the coordinates $X_S(x_{UAV(S)}, y_{UAV(S)}, z_{UAV(S)})$ are the coordinates of the unmanned aerial vehicle. Otherwise, the iterative process continues.

8. Carrying out a spectral analysis of the signals of the on-board systems of the unmanned aerial vehicle (carried out additionally if necessary).

The improved method for determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers, unlike known ones, allows for the following:

– use of signals of on-board equipment of an unmanned aerial vehicle;

– use of a network of portable spectrum analyzers;

– application of both the triangulation and the difference-ranging method for determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers;

– carrying out spectral analysis of the signals of the on-board systems of the unmanned aerial vehicle (carried out additionally if necessary).

A network of portable spectrum analyzers can be used as a separate hidden source of information about the coordinates of an unmanned aerial vehicle, or as an additional source of information about the coordinates of an unmanned aerial vehicle for radar.

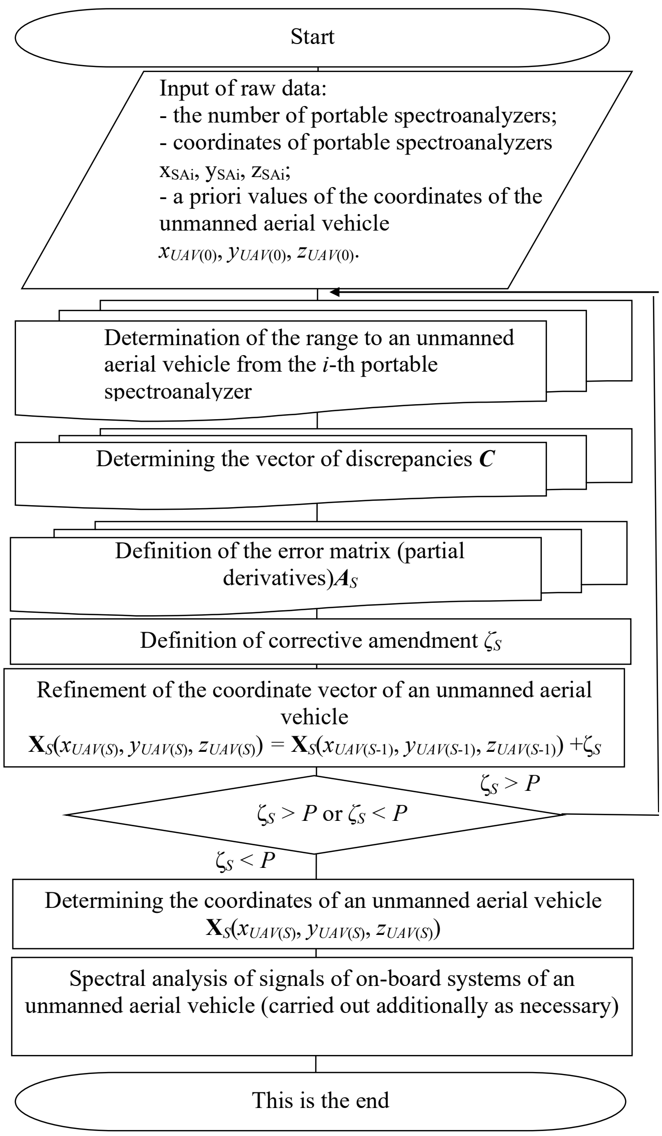

Fig. 4. Main stages of the difference-range measuring method for determining the coordinates of an unmanned aerial vehicle using a network of three portable spectrum analyzers

5. 2. Experimental research on the possibility of receiving signals with a portable spectrum analyzer

Experimental studies on the possibility of receiving signals with a portable spectrum analyzer were conducted to confirm the practical possibility of receiving signals with a portable spectrum analyzer. Initial data of experimental research:

– Tiny SA Ultra was chosen as a portable spectrum analyzer (Fig. 5). The parameters of the portable spectrum analyzer are as follows [33]:

– 4-inch screen;

– frequency range (under Ultra mode) 0.1 MHz–6 GHz;

– the possibility of switching band filters (resolution 200 Hz–850 kHz);

– built-in low-noise 20 dB amplifier;

– presence of MicroSD memory card;

– providing at least two hours of portable use without charging.

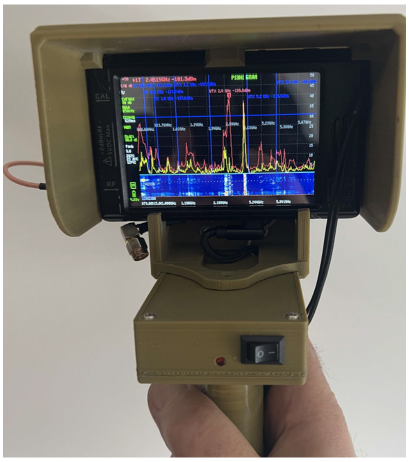

Fig. 5. Tiny SA Ultra portable spectrum analyzer

A portable spectrum analyzer uses a broadband antenna to receive signals. During the experimental research, a Vivaldi antenna or a log-periodic antenna was used (Fig. 6).

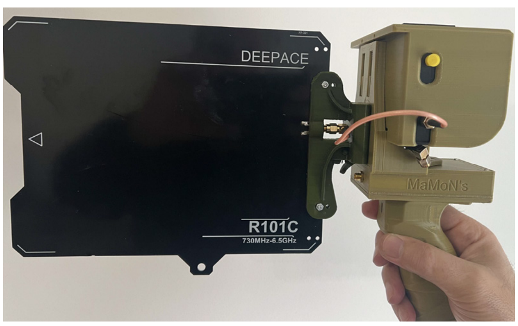

Fig. 6. The broadband antenna of the Tiny SA Ultra portable spectrum analyzer

The directional diagram of the broadband antenna (Fig. 6) was obtained using the MMANA-GAL antenna modeling software [34] and is shown in Fig. 7. The operating frequency is set to 920 MHz.

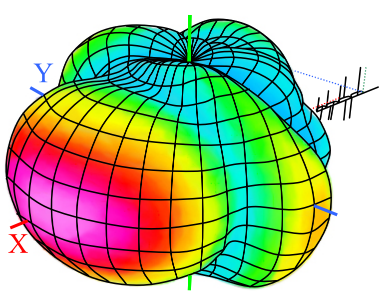

Fig. 7. Directional diagram of the broadband antenna of the Tiny SA Ultra portable spectrum analyzer was obtained using the MMANA-GAL antenna modeling software [34]

The spectrum of signals in the selected frequency range and their spectrograms are visible on the screen of the portable spectrum analyzer (Fig. 8).

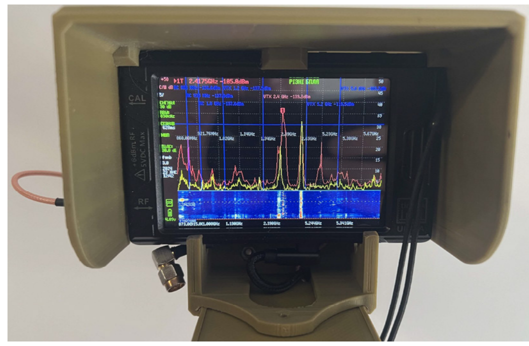

Fig. 8. Screen of a portable spectrum analyzer during an experimental study

Thus, experimental studies have shown the capabilities of a portable spectrum analyzer to receive signals and display their spectra and spectrograms.

The advantage of such portable spectrum analyzers is the availability of simple, minimal equipment. At the same time, there is a possibility of measuring the bearing to the radiation source. The disadvantage of a portable spectrum analyzer with a broadband antenna is the low directivity of such an antenna, which causes corresponding errors in determining the coordinates of an unmanned aerial vehicle.

5. 3. Evaluation of accuracy in determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers

We shall evaluate the accuracy in determining the coordinates of unmanned aerial objects by means of mathematical modeling. In this case, the method for Monte Carlo statistical tests was used.

The following limitations and assumptions were adopted during the mathematical modeling:

– portable spectrum analyzer considered – Tiny SA Ultra;

– preliminary calibration of the Tiny SA Ultra portable spectrum analyzer was carried out;

– the Tiny SA Ultra portable spectrum analyzer is set to work under an Ultra mode;

– the unmanned aerial vehicle of the tactical level "Zala" is considered as an aerial object;

– there are no obstacles to the detection of an unmanned aerial vehicle;

– signal reception by a portable spectrum analyzer from an unmanned aerial vehicle is ensured;

– portable spectrum analyzers in the network work synchronously;

– as an indicator of the accuracy in determining the coordinates of an unmanned aerial vehicle, the root mean square error was chosen;

Fig. 9, 10 show accuracy in determining the coordinates of an unmanned aerial vehicle. Fig. 9 shows the accuracy in determining the coordinates in the YX plane. Fig. 9 shows the accuracy in determining the coordinates in the YZ plane. In this case, the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 120 m.

Fig. 11 shows accuracy in determining the coordinates in the YX plane; Fig. 12 shows accuracy in determining the coordinates in the YZ plane (the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 70 m).

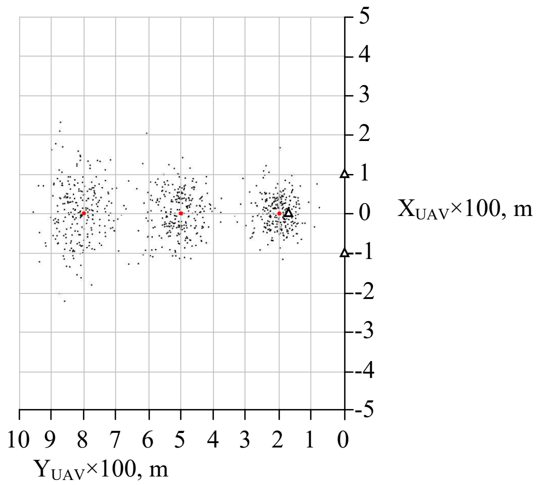

Fig. 9. Accuracy in determining the coordinates of an unmanned aerial vehicle in the YX plane (the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 120 m)

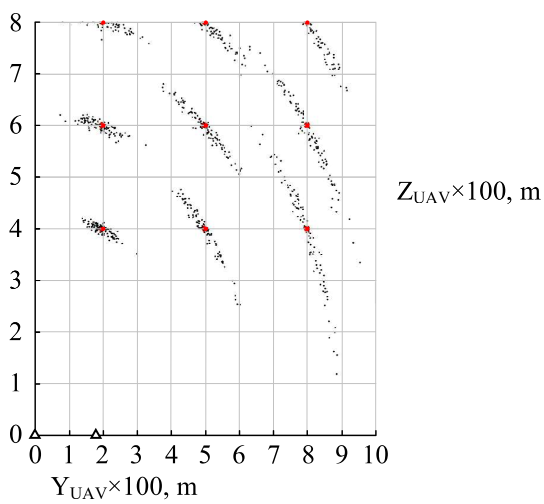

Fig. 10. Accuracy in determining the coordinates of an unmanned aerial vehicle in the YZ plane (the accuracy in determining the coordinates of one portable spectrum analyzer with a broadband antenna is 120 m)

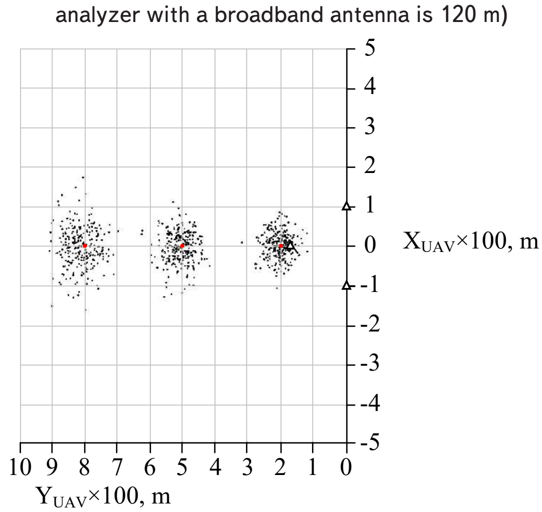

Fig. 11. Accuracy in determining the coordinates of an unmanned aerial vehicle in the YX plane (the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 70 m)

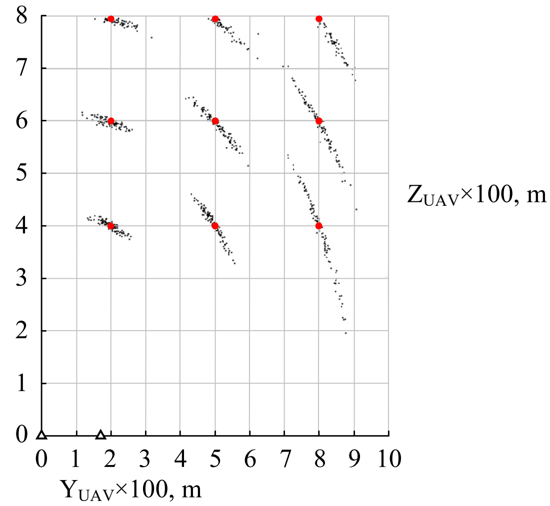

Fig. 12. Accuracy in determining the coordinates of an unmanned aerial vehicle in the YZ plane (the accuracy in determining the coordinates of one portable spectrum analyzer with a broadband antenna is 70 m)

Analysis of Fig. 9–12 has revealed the following:

– the use of a network of portable spectrum analyzers significantly reduces the root mean square error in measuring the coordinates of an unmanned aerial vehicle by approximately 50 % compared to the error of one portable spectrum analyzer;

– as the distance from the network elements of portable spectrum analyzers increases, the mean square error increases.

We shall compare the accuracy of detection of an unmanned aerial vehicle by the P-19MA radar (Ukraine) [35]. The root-mean-square errors in determining the coordinates of an unmanned aerial vehicle by the P-19MA radar station are shown in Fig. 13 [27, 35].

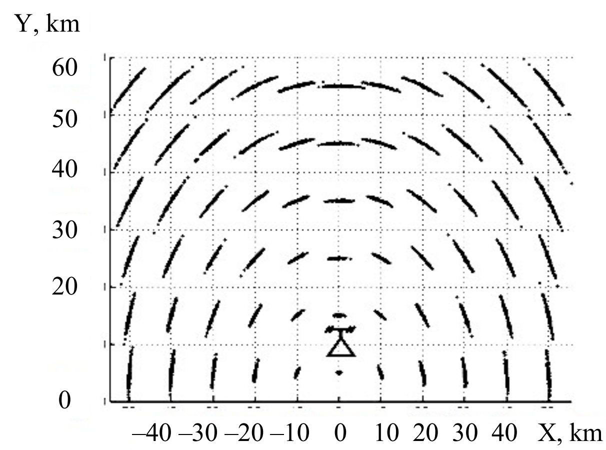

Fig. 13. Accuracy in determining the coordinates of an unmanned aerial vehicle by the P-19MA radar (the accuracy of a single measurement of the P-19MA radar is 250 m [35])

Analysis of Fig. 13 [35] demonstrates that the P-19MA radar at distances of up to 10 km ensures the accuracy in determining the coordinates of an unmanned aerial vehicle from 0.8 km to 1.3–1.5 km (with a unit measurement accuracy of 0.25 km) depending on range and angle of observation.

Analysis of Fig. 9–12 reveals that the accuracy in determining the coordinates of an unmanned aerial vehicle ranges from 0.27 km to 0.56 km, depending on the range and viewing angle of the unmanned aerial vehicle.

Analysis of Fig. 9–13 shows that the use of a network of portable spectrum analyzers reduces the root mean square error in determining the coordinates of an unmanned aerial vehicle by an average of 2.29–2.62 times compared to the P-19MA radar, depending on the range and angle of observation.

6. Discussion of results related to improving the method for determining the coordinates of inconspicuous aerial objects

We have considered a network of portable spectrum analyzers (shown in Fig. 1). Signals for determining the coordinates of an unmanned aerial vehicle can be, for example, signals of a telemetry channel, a target information delivery channel (video transmission channel), etc.

A feature of the structure of a portable spectrum analyzer is the impossibility of connecting it directly to a computer for the purpose of automated information processing. Therefore, unlike [27], the triangulation method was used to determine the coordinates of the unmanned aerial vehicle (Fig. 2).

For automated data processing, a portable spectrum analyzer must be connected to a computer. An SDR receiver [27] can be used for this purpose. In this case, the difference-range method was employed to determine coordinates of the unmanned aerial vehicle by a network of two portable spectrum analyzers (Fig. 3).

The improved method for determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers, unlike known ones, allows for the following:

– the use of signals of on-board equipment of an unmanned aerial vehicle;

– the use of a network of portable spectrum analyzers;

– application of both the triangulation and the difference-ranging method for determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers;

– carrying out spectral analysis of the signals of the onboard systems of the unmanned aerial vehicle (carried out additionally if necessary).

A network of portable spectrum analyzers can be used as a separate hidden source of information about the coordinates of an unmanned aerial vehicle, or as an additional source of information about the coordinates of an unmanned aerial vehicle for radar.

An experimental study was conducted on the possibility of receiving signals with a portable spectrum analyzer. To receive signals, the portable spectrum analyzer uses a broadband antenna (Fig. 6). The directional diagram of the broadband antenna was obtained using the MMANA-GAL antenna modeling software and is shown in Fig. 7. When conducting an experimental study, 4G network signals were detected (indicated by the number 1 in Fig. 8). The operating frequency is 2600 MHz, which fully corresponds to the operating frequency of the 4G network.

Thus, experimental studies have shown the capabilities of a portable spectrum analyzer to receive signals and display their spectra and spectrograms. The advantage of such portable spectrum analyzers is the availability of simple, minimal equipment. At the same time, there is a possibility of measuring the bearing to the radiation source. The disadvantage of a portable spectrum analyzer with a broadband antenna is the low directivity of such an antenna, which causes corresponding errors in determining the coordinates of an unmanned aerial vehicle.

The accuracy in determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers was evaluated.

We shall evaluate the accuracy in determining the coordinates of unmanned aerial objects by means of mathematical modeling. In this case, the method for Monte Carlo statistical tests was used.

Fig. 9, 10 show accuracy in determining the coordinates of an unmanned aerial vehicle. In this case, the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 120 m. Fig. 11 shows accuracy in determining the coordinates in the YX plane; Fig. 12 shows accuracy in determining the coordinates in the YZ plane (the accuracy in determining the coordinates with one portable spectrum analyzer with a broadband antenna is 70 m).

From the analysis of Fig. 9–12, the following was established:

– the use of a network of portable spectrum analyzers significantly reduces the root mean square error in measuring the coordinates of an unmanned aerial vehicle by approximately 50 % compared to the error of one portable spectrum analyzer;

– as the distance from the network elements of portable spectrum analyzers increases, the mean square error increases.

A comparison of accuracy in the identification of an unmanned aerial vehicle by the P-19MA radar (Ukraine) was performed. The root-mean-square errors in determining the coordinates of an unmanned aerial vehicle by the P-19MA radar station are shown in Fig. 13. Analysis of Fig. 9–13 reveals that the use of a network of portable spectrum analyzers reduces the root mean square error in determining the coordinates of an unmanned aerial vehicle by an average of 2.29–2.62 times compared to the P-19MA radar, depending on the range and angle of observation.

The limitations of the method include:

– its use only for detecting and measuring the coordinates of unmanned aerial vehicles;

– the method can be applied only in a network of portable spectrum analyzers;

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

The disadvantage of the method is the need to use a network of portable spectrum analyzers and the use of a broadband antenna with low directivity.

Further research is aimed at the use of antennas with a narrowed pattern.

7. Conclusions

1. The main stages of the method for determining the coordinates of an unmanned aerial vehicle using a network of portable spectrum analyzers:

– input of initial data: number of portable spectrum analyzers and their type, coordinates of portable spectrum analyzers;

– determination of the coordinates of an unmanned aerial vehicle by the triangulation method or the difference-range measuring method;

– carrying out spectral analysis of the signals of the on-board systems of the unmanned aerial vehicle (carried out additionally if necessary).

2. An experimental study was conducted on the possibility of receiving signals with a portable spectrum analyzer. Experimental studies have shown the capabilities of a portable spectrum analyzer to receive signals and display their spectra and spectrograms. The advantage of such portable spectrum analyzers is the availability of simple, minimal equipment. The disadvantage of a portable spectrum analyzer with a broadband antenna is the low directivity of such an antenna, which causes corresponding errors in determining the coordinates of an unmanned aerial vehicle.

3. Accuracy in determining the coordinates of an unmanned aerial vehicle by a network of portable spectrum analyzers was evaluated. It has been established that:

– the use of a network of portable spectrum analyzers significantly reduces the root mean square error in measuring the coordinates of an unmanned aerial vehicle by approximately 50 % compared to the error of one portable spectrum analyzer;

– as the distance from the network elements of portable spectrum analyzers increases, the mean square error increases:

– the use of a network of portable spectrum analyzers reduces the root mean square error in determining the coordinates of an unmanned aerial vehicle by an average of 2.29–2.62 times compared to the P-19MA radar, depending on the distance to the aerial object.

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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