UDC 621.396.96
DOI: 10.15587/1729-4061.2023.286466

USING SOFTWARE-DEFINED RADIO RECEIVERS FOR DETERMINING THE COORDINATES OF LOW-VISIBLE AERIAL OBJECTS

Hennadii Khudov
Corresponding author
Doctor of Technical Sciences, Professor,
Head of Department
Department of Radar Troops Tactic*
E-mail: 2345kh_hg@ukr.net
Oleksandr Kostianets
PhD, Senior Lecturer
Department of Combat Use of Radar Troops Armament*
Oleksandr Kovalenko
Doctor of Technical Sciences, Associate Professor
Department of Cybersecurity and Software
Central Ukrainian National Technical University
Universytetskyi ave., 8, Kropyvnytskyi, Ukraine, 25006
Oleh Maslenko
PhD, Senior Researcher
Scientific Research Department
Scientific-Research Institute of Military Intelligence
Yuriya Illienka str., 81, Kyiv, Ukraine, 04050
Yuriy Solomonenko
PhD, Deputy Head of the Faculty of Educational and
Scientific Work*
*Ivan Kozhedub Kharkiv National Air Force University
Sumska str., 77/79, Kharkiv, Ukraine, 61023

The object of this study is the process of determining the coordinates of low-visible aerial objects. The main hypothesis of the research assumed that the signals emitted by airborne systems of airborne objects that are not visible to radar stations have a greater power than the signal reflected from the airborne object. This, in turn, could improve the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of low-visible aerial objects. It is suggested to use Software-Defined Radio receivers to receive such signals emitted by on-board systems of low-visible aerial objects.

It was established that the main sources of signals for Software-Defined Radio receivers are signals of command, telemetry, target channels, manual control channels, and satellite navigation. It was established that an additional distinguishing feature when determining the coordinates of low-visible aerial objects is the uniqueness of their spectra and spectrograms.

The method of determining the coordinates of low-visible aerial objects when using Software-Defined Radio receivers has been improved, which, unlike the known ones, involves:

– the use as signals for Software-Defined Radio of signal receivers of on-board equipment of low-visible aerial objects;

– the use of a priori coordinate values of a low-visible aerial object;

– conducting additional spectral analysis of signals of on-board systems of low-visible aerial objects.

The spectra and spectrograms of signals of on-board systems of aerial objects when using non-directional and directional antennas were experimentally determined. The experimental studies confirm the possibility of using the Software-Defined Radio receiver to receive signals from airborne equipment and improve the signal-to-noise ratio.

The accuracy of determining the coordinates of aerial objects when using Software-Defined Radio receivers was evaluated. A decrease in the error of determining plane coordinates by the Software-Defined Radio system of receivers compared to the accuracy of determining coordinates by the P-19 MA radar station was established by an average of 1.88–2.47 times, depending on the distance to the aerial object

Keywords: low-visible aerial object, Software-Defined Radio, receiver, determination of coordinates, accuracy

Received date 12.05.2023
Accepted date 22.08.2023
Published date 30.08.2023

How to Cite: *Khudov, H., Kostianets, O., Kovalenko, O., Maslenko, O., Solomonenko, Y. (2023). Using Software-Defined Radio receivers for determining the coordinates of low-visible aerial objects. Eastern-European Journal of Enterprise Technologies, 4 (9 (124)), 61–73. doi: https://doi.org/10.15587/1729-4061.2023.286466*

1. Introduction

Modern technologies make it possible to create a new cluster of aerial objects with a small effective scattering surface [1, 2]. Such aerial objects are difficult for radar stations to detect and track. In the work, a low-visible aerial object is an aerial object whose reflected signal in the direction of the radar station is weak. This, in turn, leads to a decrease in the signal-to-noise ratio and, accordingly, makes it difficult to detect and determine the coordinates of such aerial objects. Taking into account the maneuverability of low-visible aerial objects, this additionally leads to a deterioration in the accuracy of their detection [3].

Unmanned aerial vehicles are a vivid representative of low-visible aerial objects. Unmanned aerial vehicles are used for cargo transportation, security, environmental monitoring, communication, demining, reconnaissance, surveillance, as kamikaze drones, etc. [4, 5]. The effective scattering surface of operational-level unmanned aerial vehicles (for example, "Orlan-10") when detected by radar stations is from 0.01 sq.m to 0.2 sq.m, depending on the wave range [6]. The effective dispersion surface of unmanned aerial vehicles of the tactical level (for example, "Irkut-2M"), "Zala-421") when detected by radar stations is from 0.001 sq.m to 0.01 sq.m, depending on wave range [7, 8].

The anti-aircraft defense of any state today will not be able to fully counter unmanned aerial vehicles [9, 10]. Surveillance two-coordinate radar stations of the P-18 type (Ukraine) and their variants do not provide detection and determination of the coordinates of unmanned aerial vehicles even at the operational level [10]. Three-coordinate radar stations have partial capabilities for detecting unmanned aerial vehicles of the operational level and do not detect unmanned aerial vehicles of the tactical level with the necessary requirements for detection indicators and accuracy of coordinate determination [10].

The main known methods of increasing the detection indicators and the accuracy of determining the coordinates of unmanned aerial vehicles are mainly aimed at the use of active radar methods. The coordinates of the aerial object are measured by known methods. These are range-finding, difference-range-finding, total-difference range-finding methods, etc. [10]. It is known that the accuracy of determining an arbitrary coordinate of a low-visible aerial object is determined by the error of its determination according to expression (1) [11]:

$$\sigma_R = \frac{\Delta_R}{q}, \tag{1}$$

where σ_R is the error of determining the arbitrary coordinate R; Δ_R – resolution along the R coordinate; q is the signal/noise ratio.

Therefore, taking into account expression (1) [11], known methods of improving the accuracy of determining the coordinates of low-visible aerial objects are aimed at improving the resolution of the radar station and increasing the signal/noise ratio.

Improving the resolution of a radar station is aimed at reducing the width of the antenna pattern or increasing the signal-to-noise ratio. Reducing the width of the antenna's directional pattern involves making structural changes and cannot be implemented without changing the technical characteristics of the radar station. An increase in the signal-to-noise ratio when detecting low-visible aerial objects implies an increase in the number of radar stations and an increase in their energy potential [12]. This, in turn, significantly affects the increase in the cost of creating a radar field and does not always satisfy the relevant requirements.

Therefore, finding ways to increase the signal/noise ratio when determining the coordinates of aerial objects is an urgent task. An increase in the signal/noise ratio, in turn, will lead to a decrease in the error in determining the coordinates of low-visible aerial objects.

2. Literature review and problem statement

In [13], to increase the signal/noise ratio, a method of compacting the location of radar stations is proposed. The disadvantage of [13] is a significant increase in the number of radar stations, which is difficult to implement in practice. The issue of synchronizing the operation of radar stations remained unresolved. This, in turn, does not lead to an increase in the signal-to-noise ratio.

In [14], a method of combining information from radar stations using sounding signals with different wavelengths is proposed. The disadvantage of [14] is the practical complexity of processing signals of different frequencies. Also, the issue of synchronizing the operation of radar stations of different ranges remained unresolved. This, in turn, does not lead to an increase in the signal-to-noise ratio.

In [15], the use of complex sounding signals for the detection of low-visible aerial objects is proposed. The disadvantage of [15] is the complication of algorithms for processing signals reflected from aerial objects. The question of improving the accuracy of determining the coordinates of aerial objects using complex signals remained unresolved.

In [16], the use of a network of radar stations and a method of joint processing of reflected signals are proposed. The disadvantage of [16] is the impossibility of providing a synchronous survey of the airspace when using two-coordinate survey radar stations. This, in turn, will not lead to an additive increase in the signal/noise ratio when determining the coordinates of aerial objects.

A network of two radar stations and methods of processing coherent signals from two radar stations are proposed in [17]. The disadvantage of [17] is the practical difficulty of ensuring coherent processing of signals from two radar stations. The incoherence of the processing will not make it possible to increase the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of an low-visible aerial object.

In [18], the use of spectra of signals reflected from a low-visible aerial object and methods of spectral processing are proposed. The disadvantage of [18] is the mandatory availability of a priori information about the parameters of the reflected signal, which is complicated in practice. This, in turn, does not solve the issue of increasing the accuracy of determining the coordinates of an aerial object.

In [19], the use of the Hellstrom strategy and the Petrov-Galerkin transformation is proposed. The disadvantage of [19] is the mandatory availability of a priori information about the parameters of the reflected signal. Hellstrom's strategy and the Petrov-Galerkin transformation lead to stabilization of the false alarm rate but do not allow solving the issue of increasing the signal-to-noise ratio.

In [20], the increase in the detection indicators and the accuracy of determining the coordinates of low-visible aerial objects is ensured due to the additional use of the energy of cellular communication signals. In theory, this leads to an increase in the signal-to-noise ratio. The disadvantage of [20] is the difficulty in synchronizing the operation of the radar station and cellular communication stations.

In [21], a method of joint processing of signals from two surveillance radar stations and a cellular communication station is proposed. The disadvantage of [21] is the practical difficulty of ensuring the synchronous operation of two radar stations and a cellular communication station.

In [22], the increase in the detection indicators and the accuracy of determining the coordinates of low-visible aerial objects is ensured due to the additional use of the energy of the navigation signals of space systems. An unresolved issue in [22] is the difficulty in synchronizing the operation of the radar station and the orbital grouping of navigational spacecraft.

In [23], a method of distributed reception of signals by the main and additional reception channels of one radar station is proposed. The introduction of an additional reception channel increases the signal-to-noise ratio and, accordingly, the accuracy of determining the coordinates of an aerial object. The disadvantage of [23] is the need for structural reconstruction of the radar station. This issue remains unresolved.

In [24], a model of a radar station with an additional reception channel was proposed and the detection zone of such a radar station was calculated. The introduction of an additional reception channel increases the signal-to-noise ratio and, accordingly, the accuracy of determining the coordinates of an aerial object. Unsolved in [24] is the negative impact of the penetrating signal from an additional radiation source.

In [25], the use of additional signals from onboard transponders of aerial objects is proposed. The disadvantage of [25] is only the declaration of such a possibility without carrying out appropriate mathematical calculations. The issue of practical implementation also remains unresolved [25].

Additional use of Automatic Dependent Surveillance-Broadcast (ADS-B) receivers is proposed in [26]. Additionally, the signal received by ADS-B receivers certainly increases the detection rates and the accuracy of determining the coordinates of low-visible aerial objects. The disadvantage of [26] is the mandatory presence of appropriate ADS-B transponders on the air object. Providing each air object with such a transponder is an unresolved issue.

Paper [27] proposed methods of increasing the accuracy of determining the coordinates of aerial objects, similar to those used in the United States of America's Loran-C navigation system. The disadvantage of [27] is the practical implementation of the proposed method only in navigation tasks. The issue of using methods [27] for detecting low-visible aerial objects remains unresolved.

In [28], methods of increasing the accuracy of determining the coordinates of low-visible aerial objects due to the use of the multilateration system (MLAT) are proposed. The disadvantage of [28] is the possibility of practical implementation of the method only within the boundaries of airfields and airports. The issue of synchronization of elements of the multilateration system also remains unresolved.

Study [29] proposed methods of increasing the accuracy of determining the coordinates of low-visible aerial objects by using the Wide area Multilateration (WAM) system. The disadvantage of [29] is the large distances between the receivers of the system, which requires a significant power of reflected signals from low-visible aerial objects.

In [30], a theoretical method of maximum likelihood was proposed for estimating the navigational parameters of an aerial object. The use of the method from [30] ensures obtaining estimates of the coordinates of the aerial object, which are close to the optimal ones. The disadvantage of [30] is its only theoretical focus and the need to calculate complex multidimensional objective functions.

In [31], a theoretical method of reducing the search space for target functions is proposed. The method from [31] involves the use of only quadratic objective functions. The disadvantage of [31] is obtaining statistically shifted and statistically suboptimal theoretical estimates of the coordinates of low-visible aerial objects. The issue of improving the accuracy of determining the coordinates of a low-visible aerial object remains unresolved.

In [32], additional use of the MLAT system was proposed in the detection and determination of the coordinates of an low-visible aerial object by a radar station. The disadvantage of [32] is the mandatory presence of appropriate ADS-B transponders on the air object to ensure the operation of the MLAT system. Providing each air object with such a transponder is an unresolved issue.

In [33], a method of suppressing a penetrating signal with an additional receiving channel in a radar station is proposed. The disadvantage of [33] is the complication of constructing the reception clock of the radar station. In addition, suppressing the penetrating signal also suppresses the useful signal reflected from a low-visible aerial object.

In [34], a method of constructing a radar field using a network of radar stations based on a genetic algorithm is proposed. The disadvantage of [34] is the availability of a priori information about the flight routes of low-visible aerial objects, which in practice leads to certain difficulties. The lack of a priori information, in turn, does not ensure an increase in the signal/noise ratio and the accuracy of determining the coordinates of a low-visible aerial object.

In [35], a method of integrating sources of information on unmanned aerial vehicles is proposed. The method involves the integration of information from radar sources and from sources that receive a sound signal. The disadvantage of [35] is the lack of algorithms for processing signals from unmanned aerial vehicles after their integration. The issue of increasing the signal-to-noise ratio remains unresolved.

In [36], a method of detecting objects based on the results of sound signal analysis is proposed. The sound signal can be used as an additional source of information regarding unmanned aerial vehicles, especially the Shahed type [37]. The disadvantage of [36] is the small detection range of an unmanned aerial vehicle.

Thus, the known methods of detecting and determining the coordinates of low-visible aerial objects are mainly aimed at increasing the signal/noise ratio in the radar station itself, or due to the use of several radar stations. Known methods include:

- an increase of the energy radar station;
- an increase in the number of radar stations of the same type;
- the use of radar stations of different frequency ranges;
- the use of complex probing signals;
- combining several radar stations into multi-positional systems;
- the use of methods of increasing accuracy, which are used only in active radar;
- the use of additional sources of information about low-visible aerial objects, etc.

The main disadvantages of the known methods for detecting and determining the coordinates of low-visible aerial objects are:

- a low value of the signal/noise ratio when detecting low-visible aerial objects;
- low accuracy of determining the coordinates of low-visible aerial objects by the radar station;
- low secrecy of the system's operation (especially under conditions of martial law, hybrid war, or active hostilities, for example, [37]).

The experience of repelling Russia's armed aggression against Ukraine [38, 39] confirmed that the accuracy of determining the coordinates of low-visible aerial objects should be determined taking into account the requirements for the means of their destruction (anti-aircraft missile systems, for example [40]). This fact was stated earlier in [41]. In [41], it is noted that in order to detect low-visible aerial objects, it is necessary to design radar stations that meet the following basic requirements:

– timefor updating information on aerial objects – 5 seconds;

– height range of low-visible aerial object detection – 100 m – 2–3 km;

– detection range of low-visible aerial objects – at least 120–150 km;

– the accuracy of determining the coordinates of low-visible aerial objects – units to tens of meters.

Survey radar stations of the P-18 (Ukraine), P-19 (Ukraine) type and their variants do not meet the above requirements. Therefore, it is necessary to solve the problem of increasing the signal/noise ratio when determining the coordinates of aerial objects. An increase in the signal/noise ratio, in turn, will lead to a decrease in the error in determining the coordinates of low-visible aerial objects.

3. The aim and objectives of the study

The aim of this study is to increase the accuracy of determining the coordinates of low-visible aerial objects by using the energy of signals emitted by airborne systems of low-visible aerial objects for radar stations. Such signals have a higher power than the signal reflected from an aerial object. This, in turn, will increase the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of low-visible aerial objects. It is suggested to use Software-Defined Radio receivers to receive such signals emitted by on-board systems of low-visible aerial objects. This will make it possible to improve the quality of tracking of low-visible aerial objects, ensure the stealth of work, and increase the survivability of radar stations.

To accomplish the aim, the following tasks have been set:

– to conduct a concise analysis of the main signals emitted by on-board systems of low-visible aerial objects;

– to state the main stages of the method of determining the coordinates of low-visible aerial objects when using SDR receivers;

– to conduct experimental studies on the possibility of receiving signals from low-visible aerial objects by the SDR receiver;

– to evaluate the accuracy of determining the coordinates of aerial objects when using SDR receivers.

4. The study materials and methods

The object of our study is the process of determining the coordinates of low-visible aerial objects.

The main hypothesis of the research assumed that the signals emitted by airborne systems of airborne objects that are not visible to radar stations have a greater power than the signal reflected from the airborne object. This, in turn, will increase the signal/noise ratio and, accordingly, the accuracy of determining the coordinates of low-visible aerial objects. It is suggested to use Software-Defined Radio receivers to receive such signals emitted by on-board systems of low-visible aerial objects.

The use of SDR receivers does not mean a complete rejection of the use of radar stations for the detection of low-visible aerial objects. The SDR system of receivers should be used either as an additional source for detecting and determining the coordinates of aerial objects to the radar station, or as a separate system that issues preliminary target designations to radar devices. The use of the SDR system of receivers will reduce the time of operation of radar stations and, accordingly, ensure the stealth of operation and increase the survivability of the radar station. This is especially important in the context of modern wars and armed conflicts.

The following research methods were used during our study:

– mathematical apparatus of matrix theory;

– radar location methods;

– methods of digital signal processing;

– methods of probability theory and mathematical statistics;

– methods of system analysis;

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

– iterative methods;

– differential calculus methods;

– methods of multi-position radar;

– methods of mathematical modeling.

During the study, the following limitations and assumptions were made:

– radar stations are limited to P-18MA (Ukraine), P-18MU (Ukraine), P-18 “Malachite” (Ukraine) radar stations;

– radio receiving devices of radar stations are digital;

– unmanned aerial vehicles are considered low-visible aerial objects;

– when determining the characteristics of the main signals emitted by on-board systems of low-visible aerial objects, the Orlan-10 is considered as an example;

– it is assumed that there are no obstacles;

– it is assumed that reception of the SDR signal by receivers is ensured;

– SDR receivers in the system work synchronously;

– the Monte Carlo statistical test method is used for modeling;

– experimental studies were conducted with a DVB-T+FM+DAB 820T2 & SDR receiver.

5. Results of research on improving the method for determining the coordinates of low-visible aerial objects

5. 1. Brief analysis of the main signals emitted by on-board systems of low-visible aerial objects

The necessity of posing and solving the problem of analyzing the signals emitted by on-board systems of low-visible aerial objects is due to the proof of the possibility of using such signals to increase the signal-to-noise ratio. This, in turn, leads, according to expression (1), to an increase in the accuracy of determining the coordinates of low-visible aerial objects.

The main sources of signals for SDR receivers are the signals of the following channels of the unmanned aerial vehicle:

– command (the flight route is adjusted, the operating modes of the target equipment are changed, etc.);

– telemetric (data on flight route coordinates, on-board equipment operating modes);

– issuance of target information (signals from the on-board camera);

– manual control (at the stage of take-off and landing);

– satellite navigation (navigation, GPS or GLONASS signals).

The main unmasking feature of the target information delivery channel signal is its relatively large (1–10 MHz) spectrum width. This is due to the need to ensure a high speed of target information transmission. Features of other UAV channels:

– low data transfer speed;

– relatively small (0.3 MHz) spectrum width;

– the presence of carrier frequency changes in telemetry channel signals, as a rule, jump-like and periodic (pseudo-random tuning of the operating frequency (PSR)).

For example, Table 1 gives the main characteristics of signals of the telemetry channel of the Orlan-10 unmanned aerial vehicle. Information for Table 1 is compiled from [6, 42, 43].

Fig. 1 shows the spectrum and spectrogram of the telemetry channel signal of the Orlan-10 unmanned aerial vehicle as an example. Fig. 1 was obtained based on the results of the analysis [6, 42, 43]. The term “spectrogram” refers to an image that highlights the dependence of the spectral density of the signal power on time(for example, [44, 45]).

In Fig. 1, the spectrum and spectrogram were obtained under the condition of a spectrum width of 1 MHz at frequencies from 921 MHz to 922 MHz. From the analysis of Fig. 1, it can be concluded that the signal-to-noise ratio for telemetry channel signals is approximately 24 dB. It is known [6, 12–14] that when the Orlan-10 UAV is detected by radar stations of the P-18MA, P-19 MA type, the average is from 8 dB to 13 dB, depending on the detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

For example, Table 2 gives the main characteristics of the signals of the telemetry channel of the Eleron-3SV unmanned aerial vehicle. Information for Table 2 was obtained from [46].

Fig. 2 shows the spectrum and spectrogram of the telemetry channel signal of the Eleron-3SV unmanned aerial vehicle as an example. Fig. 2 was obtained based on the results of the analysis [46].

Table 1

The main characteristics of signals of the telemetry channel of the Orlan-10 unmanned aerial vehicle [6, 42, 43]

The name of the signal parameter	Frequency range, MHz	Signal spectrum width, MHz	Number of frequencies for FHSS	Number of frequency hops per second, times	Pitch of the grid of frequencies at which FHSS is performed	The structure of the accumulated signal
Parameter value	900–922	2.2	11	25	0.2	uniform
		7	35			
		1	5			
		4.5	22.5			
		20	100			

Table 2

The main characteristics of signals of the telemetry channel of the Eleron-3SV unmanned aerial vehicle [46]

The name of the signal parameter	Frequency range, MHz	Signal spectrum width, MHz	Number of frequencies for FHSS	Number of frequency hops per second, times	Pitch of the grid of frequencies at which FHSS is performed	The structure of the accumulated signal
Parameter value	915–920	5	10	5	0,29	not uniform

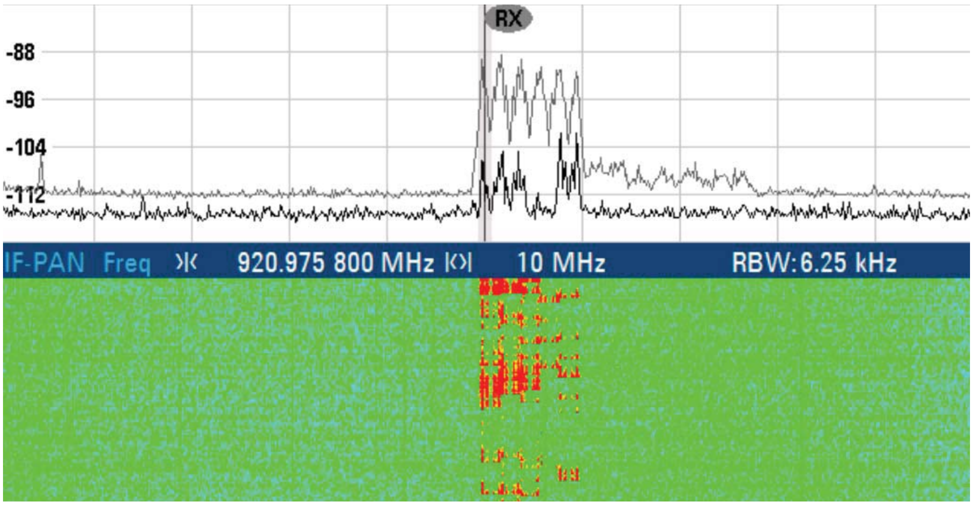


Fig. 1. Spectrum and spectrogram spectrogram of the telemetry channel signal of the Orlan-10 unmanned aerial vehicle [6, 42, 43]

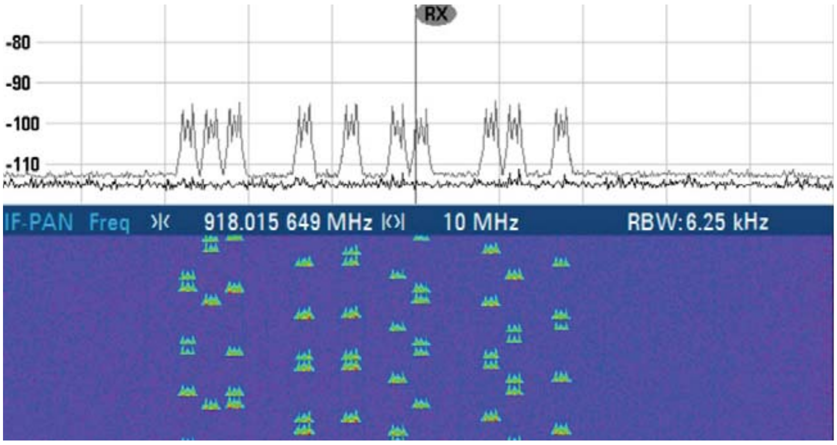


Fig. 2. Spectrum and spectrogram of the telemetry channel signal of the Eleron-3SV unmanned aerial vehicle [46]

In Fig. 2, the spectrum and spectrogram were obtained under the condition of using 10 frequencies in the band from 915 MHz to 920 MHz. From the analysis of Fig. 2, it can be concluded that the signal-to-noise ratio for telemetry channel signals is approximately 17 dB. It is known [8, 12–14] that when the Eleron-3SV unmanned aerial vehicle is detected by radar stations of the P-18 MA, P-19MA type, it averages from 6 dB to 12 dB, depending on the detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

Therefore, the above signals from the on-board equipment of unmanned aerial vehicles can be the main sources of signals for SDR receivers. Analysis of Tables 1, 2 reveals the difference in spectra and spectrograms of various unmanned aerial vehicles, which can be an additional distinguishing feature when determining the coordinates of unmanned aerial vehicles.

5. 2. The main stages of the method for determining the coordinates of stealth air objects

A system of three SDR receivers was considered (Fig. 3). This is the minimum required number of SDR receivers for determining the coordinates of an aerial object using the passive difference-range-finding method (for example, [11, 13, 22, 31]). The number of receivers in operation is not optimized in the work: this is the subject of further research. Each SDR receiver receives signals from the aircraft's on-board systems.

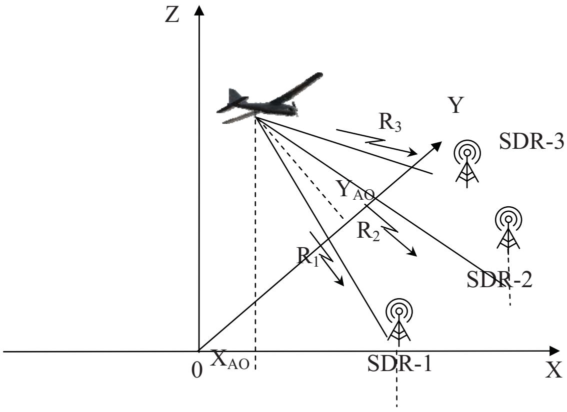


Fig. 3. System of three SDR receivers

Fig. 3 shows a low-visible aerial object (Orlan-10 unmanned aerial vehicle). The coordinates of the aerial object in Fig. 3 are marked X_{AO}, and Y_{AO}. Also, in Fig. 3, we marked three SDR receivers (SDR-1, SDR-2, SDR-3). For simplicity and clarity, the Cartesian coordinate system XYZ is considered (the axes of the system are marked in Fig. 3).

SDR receivers receive signals from on-board systems of low-visible aerial objects. The task of determining the coordinates of a low-visible aerial object in the SDR receiver system is set. To solve the task, known difference-distance measuring method is used [47]. When explaining the essence of the method, the results from [33, 48] were used.

So, the difference-ranging method involves calculating the coordinates of a low-visible aerial object by constructing lines from each SDR receiver to a low-visible aerial object and finding the intersection point of these lines [33, 48]. In each SDR receiver, in general, the difference in the arrival timeof signals from an aerial object to each of the SDR receivers $\Delta\tau_{ij}(\alpha, \beta_i, \beta_j)$ is measured. The symbol α denotes the coordinate vector of an unmanned aerial vehicle (low-visible aerial object). The symbols β_i, β_j denote the coordinate vectors of the *i*-th and *j*-th SDR receiver. In general, it can be assumed that the number of SDR receivers is *N*.

The difference-ranging method makes it possible to determine the distance differences $\Delta R_{ij}(\alpha, \beta_i, \beta_j)$ from a low-visible aerial object to each SDR receiver (expression (2)) [33, 48]:

$$\Delta R_{ij}(\alpha, \beta_i, \beta_j)=c\Delta\tau_{ij}(\alpha, \beta_i, \beta_j), \tag{2}$$

where *c* is the speed of light.

If we take into account the Cartesian coordinate system and write the coordinates vectors of a low-visible aerial object in the form $\alpha(x_{AO}, y_{AO}, z_{AO})$, and the SDR coordinate vectors of the receivers in the form $\beta_i(x_i, y_i, z_i)$, $\beta_j(x_j, y_j, z_j)$, then, taking into account the above, expression (1) can be rewritten as expression (3) [33, 48]:

$$\begin{aligned}\Delta R_{ij} &= R_i - R_j = \\ &= \sqrt{\left[\left(x_i - x_{AO}\right)^2 + \left(y_j - y_{AO}\right)^2 + \left(z_j - z_{AO}\right)^2\right]} + \\ &+ \Delta R_i - \sqrt{\left[\left(x_j - x_{AO}\right)^2 + \left(y_j - y_{AO}\right)^2 + \left(z_j - z_{AO}\right)^2\right]} - \\ &- \Delta R_j = c \cdot \Delta\tau_{ij}.\end{aligned} \tag{3}$$

By analogy with [33, 48], it is assumed that one of the SDR receivers is the reference (its index is zero), and all distance differences are calculated with respect to this reference SDR receiver. This makes it possible to denote the distance difference by the symbol ΔR_i instead of the symbol $\Delta R_{ij}(\alpha, \beta_i, \beta_j)$. It also takes into account the well-known fact that the number of independent differences in the moments of arrival of signals of on-board systems is equal to $(N-1)$.

From the analysis of expression (3) it follows that four quantities are unknown, namely:

– coordinates of a low-visible aerial object x_{AO}, y_{AO}, z_{AO} (three unknowns);

– the unknown distance difference $\Delta R_{\sin}=\Delta R_i-\Delta R_j$, which is caused by the asynchrony of the timescales of the SDR receivers.

The above does not allow solving the system of nonlinear equations (expression (3)) by analytical methods. Therefore, hereafter, we shall use iterative methods to determine the coordinates of a low-visible aerial object. Such methods have proven efficient in the application of swarm optimization methods, for example, [49, 50].

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers are shown in Fig. 4.

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers:

1. Input of initial data: the number of SDR receivers; coordinates of SDR receivers x_i, y_i, z_i; a priori values of the coordinates of a low-visible aerial object $x_{AO(0)}$, $y_{AO(0)}$, $z_{AO(0)}$ (initial approximations).

2. Calculation of the range to an aerial object from the i-th SDR receiver (expression (4)):

$$R_i=\sqrt{\left[\left(x_i-x_{\mathrm{AO}(0)}\right)^2+\left(y_i-y_{AO(0)}\right)^2+\left(z_i-z_{AO(0)}\right)^2\right]}. \quad (4)$$

3. Calculation of the vector of discontinuities C at the S-th iteration (expression (5)):

$$C_{i(S)}=(R_{i(S-1)}-R_{S-1}-(T_i-T))c;$$

$$i=1, \ldots, (S-1), \tag{5}$$

where the symbols $R_{i(S-1)}$, R_{S-1} denote the distances from the i-th and 0-th SDR receiver to the point with coordinates $x_{T(0)}$, $y_{T(0)}$, $z_{T(0)}$. The distances $R_{i(S-1)}$, and R_{S-1} are calculated for each of the $(S-1)$ iterations; the difference (T_i-T) means the difference in the reception timeof the i-th and 0-th SDR signals by the receiver; c is the speed of light.

4. Calculation of the matrix of partial derivatives $\boldsymbol{A}_S$ according to expression (6):

$$A_{\mathrm{i}1(\mathrm{x})}=\frac{\partial R_i\left(x_{AO(S)},y_{AO(S)},z_{AO(S)}\right)}{\partial x_{AO(S)}},$$

$$A_{\mathrm{i}2(\mathrm{x})}=\frac{\partial R_i\left(x_{AO(S)},y_{AO(S)},z_{AO(S)}\right)}{\partial y_{AO(S)}},$$

$$A_{\mathrm{i}3(\mathrm{x})}=\frac{\partial R_i\left(x_{AO(S)},y_{AO(S)},z_{AO(S)}\right)}{\partial z_{AO(S)}}. \tag{6}$$

5. Definition of corrective correction ζ_S (expression (7)):

$$\zeta_{\mathrm{S}}=\left(\left(A_{S-1}\right)^T RA_{S-1}\right)^{-1}\left(A_{S-1}\right)^T RC. \tag{7}$$

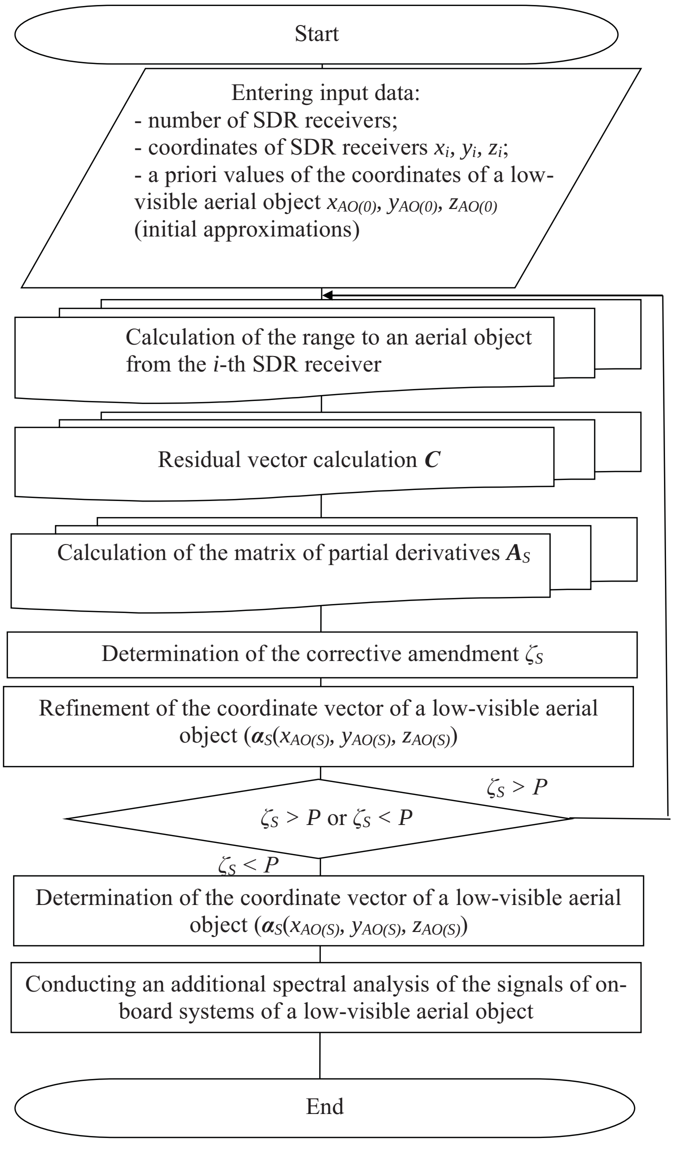


Fig. 4. The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers

6. Clarification of the coordinate vector of a stealth air object ($\alpha_S(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})$) (expression (8)):

$$\alpha_S(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})=\alpha_S(x_{AO(S\text{-}1)}, y_{AO(S\text{-}1)},$$

$$z_{AO(S\text{-}1)})+\zeta_S. \tag{8}$$

7. Checking the conditions ($\zeta_S>P$) or ($\zeta_S<P$). If ($\zeta_S<P$), the iterative process ends, ($\alpha_S(x_{AO(S)}, y_{AO(S)}, z_{AO(S)})$ is taken as the estimate of the coordinates of the low-visible aerial object). If ($\zeta_S>P$), the iterative process continues.

8. Conducting an additional spectral analysis of the signals of on-board systems of a low-visible aerial object. Such an analysis is carried out in order to determine the type of low-visible aerial object based on the data of the spectral analysis of the signals of its on-board equipment. To this end, for example, the data from Tables 1, 2 can be used, as well as Fig. 1, 2, etc. It is the use of spectral analysis and spectrograms of signals that, in addition to increasing the accuracy of coordinate determination, allows us to determine the type of low-visible aerial object.

Thus, in contrast to known methods, the improved method for determining the coordinates of low-visible aerial objects when using SDR receivers implies:

– the use as signals for SDR of signal receivers of on-board equipment of low-visible aerial objects;

– the use of a priori values of the coordinates of a low-visible aerial object $x_{AO(0)}$, $y_{AO(0)}$, $z_{AO(0)}$;

– conducting additional spectral analysis of signals of on-board systems of low-visible aerial objects.

The SDR system of receivers can be used as a separate source of information about the coordinates of a low-visible aerial object, or as an additional source of information about the coordinates of a low-visible aerial object to the main radar station.

5. 3. Experimental studies on the possibility of receiving signals by the SDR receiver

We shall conduct experimental studies to confirm the practical possibility of receiving SDR signals by the receiver of onboard systems of aerial objects. Initial data for conducting experimental studies:

– the place of experimental research is the city of Kharkiv (Ukraine);

– the DVB-T+FM+DAB 820T2 & SDR receiver was chosen as the SDR receiver (Fig. 5). The characteristics and parameters of the receiver are as follows [27].

Technical characteristics of the receiver:

– frequency range: 24–1900 MHz;

– sensitivity: 220 mV;

– dynamic range: 50db;

– bandwidth: 0.25–3 MHz;

– bit rate of analog-digital converter: 8 bits;

– interface: USB 2.0;

– the software AIRSPY (USA) [51] was chosen as the software when working with the SDR receiver;

– as a directional antenna, a director antenna [52] with characteristics and parameters is chosen:

– operating frequency, 1080 MHz;

– wavelength, 0.278 m;

– number of elements, 5;

– antenna length, 0.238 m;

– coefficient of directional action, 8.56;

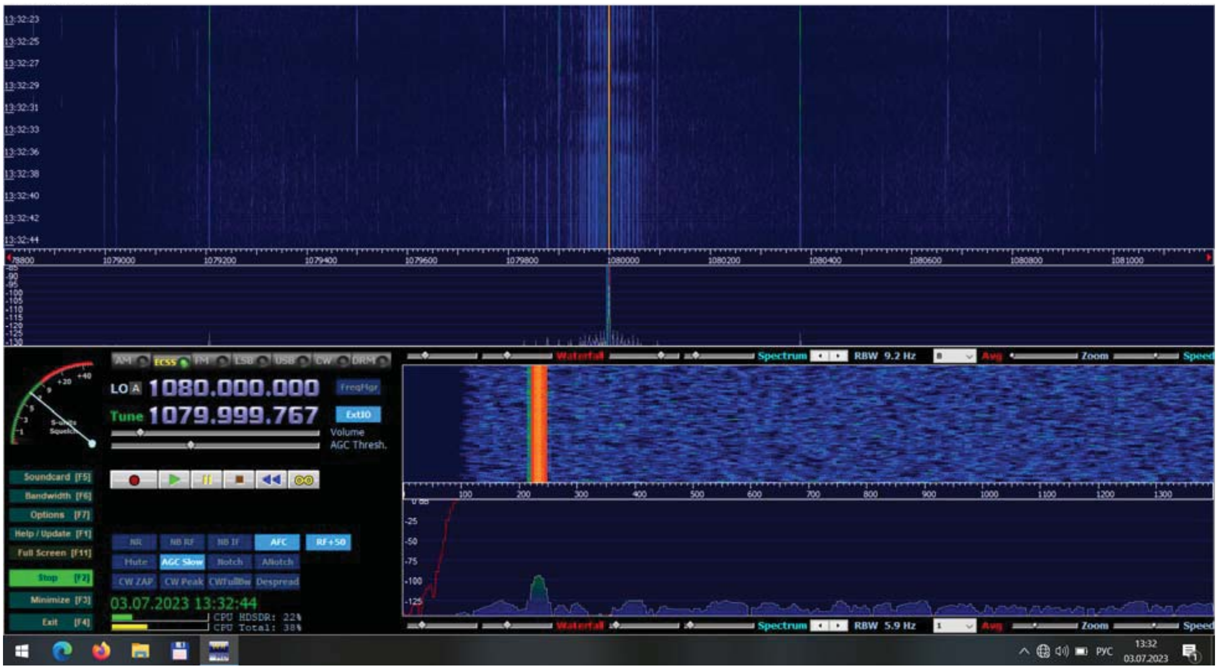
– the width of the directional diagram is 92°.

Experimental installation using a non-directional antenna is shown in Fig. 6.

The spectrum and spectrogram of the received signal when using a non-directional antenna are shown in Fig. 7.

Fig. 5. Receiver DVB-T+FM+DAB 820T2 & SDR with non-directional antenna 15 cm (included)

Fig. 6. Experimental installation using a non-directional antenna



LO A 1080.000.000

Tune 1079.999.767

03.07.2023 13:32:44

CPU HDSDR: 22%

CPU Total: 38%

RBW 9.2 Hz

RBW 5.9 Hz

Fig. 7. Spectrum and spectrogram of the received signal when using a non-directional antenna

Taking into account the information from Fig. 7, it can be assumed that this is an ADS-B signal of a Russian aerial object (civilian or military). A more detailed analysis and determination of the type of aerial object can be carried out using the results of [26, 27] but this is beyond the scope of this work.

The experimental setup using a directional antenna is shown in Fig. 8.

Fig. 8. Experimental installation using a directional antenna

The spectrum and spectrogram of the received signal when using a directional antenna are shown in Fig. 9.

Taking into account the information from Fig. 9, it can be assumed that this is also an ADS-B signal of a Russian aerial object (civilian or military). With the help of a directional antenna, you can indicate the direction of an aerial object (bearing). A more detailed analysis and determination of the type of aerial object can be carried out using the results of [26, 27] but this is beyond the scope of this work.

Thus, our experimental studies confirm the possibility of using the SDR receiver to receive signals from the on-board equipment of aerial objects. A more detailed analysis and determination of the type of aerial object can be carried out using the results of [26, 27] but this is beyond the scope of this work and is the subject of further research.

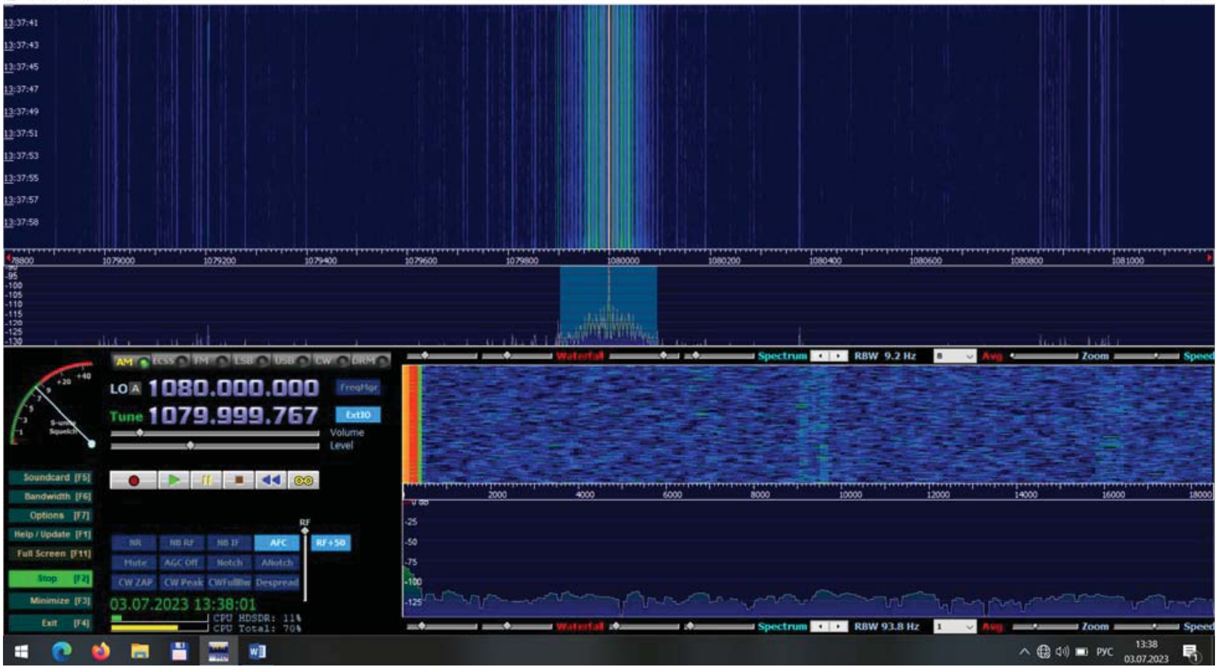
5. 4. Evaluation of the accuracy of determining the coordinates of air objects when using SDR receivers

We shall assess the accuracy of determining the coordinates of aerial objects by means of mathematical modeling using Monte Carlo statistical tests. At the same time, we shall use the results of [33].

Three identical SDR receivers were used, one of which is the reference, and the other two are located at a distance of 5 km from the reference. The error of the unit measurement of the plane coordinates of the aerial object along the X and Y axes is the same and is 30 m. Fig. 10 shows an assessment of the accuracy of determining the plane coordinates of an aerial object by the method of Monte Carlo statistical tests. The mean square error of determining the plane coordinates of an aerial object was chosen as an indicator of the accuracy of determining the plane coordinates.

To carry out a comparative assessment of the accuracy of determining the coordinates of an aerial object, we shall conduct a simulation of determining the coordinates of an aerial object by a single-position radar station. The radar station P-19MA (Ukraine) was considered [53]. The root mean square error of a single measurement for the P-19MA radar station is 250 m [53]. To measure the coordinates of an aerial object in the P-19MA radar station, the angular-range-measuring method is used [53]. The results of the assessment of the plane coordinates of the aerial object by the P-19MA radar station are shown in Fig. 11.

The MATLAB application package, version R2017b, was used to assess the accuracy of determining plane coordinates (Fig. 10, 11).



LO A 1080.000.000

Tune 1079.999.767

03.07.2023 13:38:01

CPU HDSDR: 11%

CPU Total: 70%

Fig. 9. Spectrum and spectrogram of the received signal when using a directional antenna

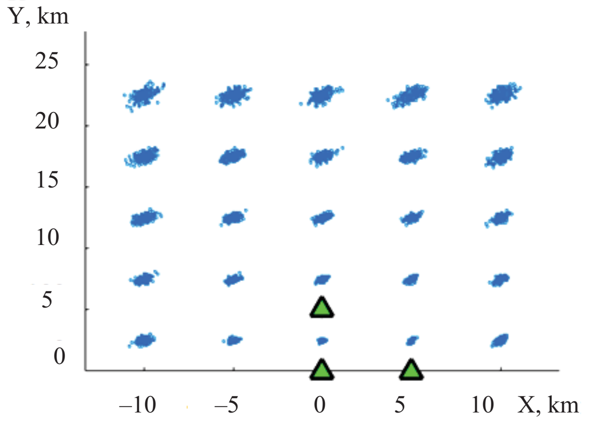


Fig. 10. Estimation of the accuracy of determining the planar coordinates of an air object by a system of three SDR receivers

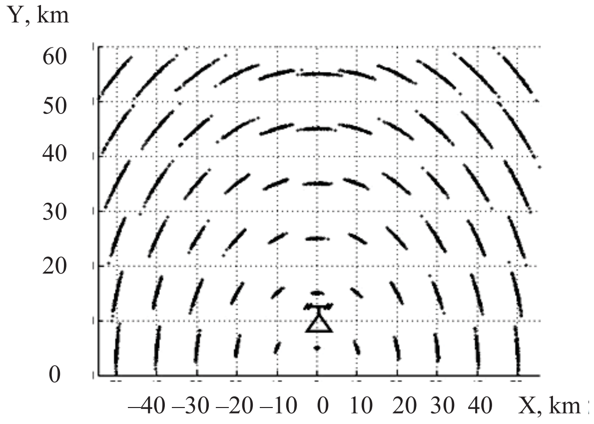


Fig. 11. Estimation of plane coordinates of an air object by P-19MA radar station

Analysis of Fig. 10, 11 shows a decrease in the error of determining plane coordinates by the SDR system of receivers in comparison with the accuracy of determining coordinates by the P-19MA radar station by an average of 1.88–2.47 times, depending on the distance to the aerial object.

It should be noted that the accuracy of determining the coordinates of low-visible aerial objects by the SDR receiver system significantly depends on the synchronization of the SDR receivers. For high-quality and accurate synchronization, the exact timing should not exceed 50 ns [25]. Such timebinding can be ensured in the following ways:

1. Using Global Position System (GPS) receivers.
2. Additional use of SDR transceiver HackRf One [54].
3. Use as reference ADS-B signals from aerial objects with known coordinates.

This method of synchronizing SDR receivers is discussed in more detail below for an example. It involves the following sequence of actions:

– reception of messages (signals) from aerial objects equipped with ADS-B equipment;

– attaching the timevalues of each SDR receiver to each message of the ADS-B equipment;

– data transfer to the information processing point (one of the receivers can act as a processing point);

– calculation of the difference in signal arrival timeaccording to ADS-B data and the difference in signal arrival timeaccording to SDR receiver data;

– calculation of timecorrection;

– adjustment (synchronization) of SDR receivers taking into account the timecorrection for each of them.

6. Discussion of results of improving the method for determining the coordinates of stealth air objects

A concise analysis of the main signals emitted by airborne systems of low-visible aerial objects has been carried out. Our analysis has made it possible to substantiate the possibility of using such signals to increase the signal/noise ratio due to the use of the SDR receiver system. It is the SDR receivers that are the consumers of the signals of on-board systems of low-visible aerial objects. This, in turn, leads, according to expression (1), to an increase in the accuracy of determining the coordinates of low-visible aerial objects.

It was established that the main sources of signals for SDR receivers are signals of command, telemetry, target channels, manual control channels and satellite navigation. Examples of the main characteristics of signals of the telemetry channel of unmanned aerial vehicles “Orlan-10” and “Eleron” are given in Tables 1, 2. Examples of spectra and spectrograms of the signals of the telemetry channel of the Orlan-10 and Eleron unmanned aerial vehicles are shown in Fig. 1, 2. From the analysis of Fig. 1, 2, it can be concluded that the signal-to-noise ratio for telemetry channel signals ranges from 17 dB to 24 dB, depending on the type of unmanned aerial vehicle. When unmanned aerial vehicles are detected by radar stations of the P-18MA, P-19 MA type, the signal-to-noise ratio ranges from 6 dB to 13 dB on average, depending on the type of aircraft and detection conditions. This indicates an increase in the signal/noise ratio due to the use of on-board equipment signals of low-visible aerial objects.

In contrast to known results, for example, [22, 23], it is proposed to use the signals of on-board equipment of unmanned aerial vehicles as the main sources of signals for SDR receivers. Analysis of Tables 1, 2 reveals the difference in the spectra and spectrograms of different UAVs, which can be an additional distinguishing feature of UAVs.

The use of SDR receivers does not mean a complete rejection of the use of radar stations for the detection of low-visible aerial objects. The SDR system of receivers should be used either as an additional source for detecting and determining the coordinates of aerial objects to the radar station, or as a separate system that issues preliminary target designations to radar devices. The use of the SDR system of receivers will reduce the timeof operation of radar stations and, accordingly, ensure the stealth of operation and increase the survivability of the radar station. This is especially important in the context of modern wars and armed conflicts.

The main stages of the method for determining the coordinates of low-visible aerial objects when using SDR receivers are given in Fig. 4. The method for determining the coordinates of low-visible aerial objects when using SDR receivers has been improved, which, unlike the known ones, providesfor the following:

– the use as signals for SDR of signal receivers of on-board equipment of low-visible aerial objects;

– the use of a priori coordinate values of a low-visible aerial object;

– conducting additional spectral analysis of signals of on-board systems of low-visible aerial objects.

The features of the improved method are the use of SDR receivers and additional spectral analysis of the signals of the onboard systems of the aerial object. The use of spectral analysis and spectrograms of signals makes it possible to determine the type of low-visible aerial object in addition to increasing the accuracy of coordinate determination.

To confirm the practical possibility of SDR reception by the receiver of signals of onboard systems of aerial objects, experimental studies were carried out. The spectrum and spectrogram of the received signal when using a non-directional antenna are shown in Fig. 7. The spectrum and spectrogram of the received signal when using a directional antenna are shown in Fig. 9. Taking into account the information in Fig. 7, 9, it can be assumed that these are ADS-B signals of a Russian aerial object (civilian or military). With the help of a directional antenna, you can indicate the direction of an aerial object (bearing). A more detailed analysis and determination of the type of air object is beyond the scope of this work. Our experimental studies confirm the possibility of using the SDR receiver to receive signals from on-board equipment of aerial objects and increase the signal-to-noise ratio. This, in turn, leads to an increase in the accuracy of determining the coordinates of low-visible aerial objects.

The accuracy of determining the coordinates of aerial objects when using SDR receivers was evaluated. We shall assess the accuracy of determining the coordinates of aerial objects by means of mathematical modeling using Monte Carlo statistical tests. Analysis of Fig. 10, 11 reveals a decrease in the error of determination of plane coordinates by the SDR system of receivers in comparison with the accuracy of determination of coordinates by the P-19MA radar station [53] by an average of 1.88–2.47 times, depending on the distance to the aerial object. This becomes possible thanks to the use of the SDR receiver system.

Synchronization of SDR receivers can be ensured in the following ways.

1. Using GPS receivers.
2. Additional use of SDR transceiver HackRf One [54].
3. Use as reference ADS-B signals from aerial objects with known coordinates.

The improved method of determining the coordinates of aerial objects when using SDR receivers can be applied in airspace control in peacetime and wartime conditions to increase the survivability of radar stations.

The limitations of the method are:

– in its use only for detecting and measuring the coordinates of low-visible aerial objects. Air objects with a sufficiently large effective scattering surface (1 m^2 and above) are detected by a radar station;

– the method can be applied only in the system of digital SDR receivers;

– the work does not take into account the influence of interference and means of radio-electronic warfare. Consideration of these factors is the subject of further research.

An important aspect is also the choice of the type and model of SDR receivers according to the price-quality criterion. This aspect is not considered in the work.

The disadvantage of the method is the need to use several SDR receivers and the need to synchronize the operation of SDR receivers.

Further research is aimed at creating a database of signals of on-board systems of low-visible aerial objects for the purpose of their further recognition.

7. Conclusions

1. A concise analysis of the main signals emitted by airborne systems of low-visible aerial objects has been carried out. It was established that the main sources of signals for SDR receivers are signals of command, telemetry, target channels, manual control channels and satellite navigation. It was established that an additional distinguishing feature is the difference in the spectra and spectrograms of various unmanned aerial vehicles.

2. The method for determining the coordinates of low-visible aerial objects when using SDR receivers has been improved, which, unlike known ones, provides for the following:

– the use as signals for SDR of signal receivers of on-board equipment of low-visible aerial objects;

– the use of a priori coordinate values of a low-visible aerial object;

– conducting additional spectral analysis of signals of on-board systems of low-visible aerial objects.

3. We have experimentally determined the spectra and spectrograms of the received signal when using non-directional and directional antennas. Our experimental studies confirm the possibility of using the SDR receiver to receive signals from the on-board equipment of aerial objects.

4. The accuracy of determining the coordinates of aerial objects when using SDR receivers was evaluated. A decrease in the error of determining plane coordinates by the SDR system of receivers compared to the accuracy of determining coordinates by the P-19MA radar station was established by an average of 1.88–2.47 times, 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 and the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

References

1. Erl, J. (2022). Sensing digital objects in the air: Ultraleap introduces new technology. Available at: https://mixed-news.com/en/sensing-digital-objects-in-the-air-ultraleap-introduces-new-technology/
2. Sample, I. (2023). What do we know about the four flying objects shot down by the US? Available at: https://www.theguardian.com/world/2023/feb/13/what-do-we-know-about-the-four-flying-objects-shot-down-by-the-us
3. Carafano, J. J. (2022). Rapid advancements in military tech. Available at: https://www.gisreportsonline.com/r/military-technology
4. Stilwell, B. (2023). 4 Amazing Military Aviation Technologies We'll See in the Near Future. Available at: https://www.military.com/off-duty/4-amazing-military-aviation-technologies-well-see-near-future.html
5. Globa, L., Dovgyi, S., Kopiika, O., Kozlov, O. (2022). Approach to Uniform Platform Development for the Ecology Digital Environment of Ukraine. Lecture Notes in Networks and Systems, 83–100. doi: https://doi.org/10.1007/978-3-031-16368-5_4
6. Orlan-10 Uncrewed Aerial Vehicle (UAV). Available at: https://www.airforce-technology.com/projects/orlan-10-unmanned-aerial-vehicle-uav/#catfish
7. Russia behind the UAV technology curve (2021). Available at: https://issuu.com/edrmag/docs/edr_58_-_web/s/12783061
8. Chang, L. ZALA Lancet. Loitering munition. Available at: https://www.militarytoday.com/aircraft/lancet.htm
9. Chopra, A. (2022). Next gen military technologies. Available at: https://www.sps-aviation.com/story/?id=3161&h=Next-Gen-Military-Technologies
10. Wang, H., Cheng, H., Hao, H. (2020). The Use of Unmanned Aerial Vehicle in Military Operations. Lecture Notes in Electrical Engineering, 939–945. doi: https://doi.org/10.1007/978-981-15-6978-4_108
11. Richards, M. A., Scheer, J. A., Holm, W. A. (2010). Principles of modern radar. Vol. I. Basic principles. Raleigh: SciTech Publishing, 924. doi: https://doi.org/10.1049/sbra021e
12. Khudov, H., Zvonko, A., Kovalevskyi, S., Lishchenko, V., Zots, F. (2018). Method for the detection of small¬sized air objects by observational radars. Eastern-European Journal of Enterprise Technologies, 2 (9 (92)), 61–68. doi: https://doi.org/10.15587/1729-4061.2018.126509
13. Melvin, W. L., Scheer, J. A. (2013). Principles of modern radar. Vol. II. Advanced techniques. Raleigh: SciTech Publishing, 846. doi: https://doi.org/10.1049/sbra020e
14. Melvin, W. L., Scheer, J. A. (2014). Principles of modern radar. Vol. III. Radar applications. Raleigh: SciTech Publishing, 820. doi: https://doi.org/10.1049/sbra503e
15. Bezouwen, J., Brandfass, M. (2017). Technology Trends for Future Radar. Available at: https://www.microwavejournal.com/articles/29367-technology-trends-for-future-radar
16. Lishchenko, V., Kalimulin, T., Khizhnyak, I., Khudov, H. (2018). The Method of the organization Coordinated Work for Air Surveillance in MIMO Radar. 2018 International Conference on Information and Telecommunication Technologies and Radio Electronics (UkrMiCo). doi: https://doi.org/10.1109/ukrmico43733.2018.9047560
17. Khudov, H. et. al. (2020). The Coherent Signals Processing Method in the Multiradar System of the Same Type Two-coordinate Surveillance Radars with Mechanical Azimuthal Rotation. International Journal of Emerging Trends in Engineering Research, 8 (6), 2624–2630. doi: https://doi.org/10.30534/ijeter/2020/66862020
18. Marpl-ml, S. L. (1990). Tsifrovoy spektral'niy analiz i ego. Mosocw: Mir, 584.
19. Klimov, S. A. (2013). Metod povysheniya razreshayuschey sposobnosti radiolokatsionnykh sistem pri tsifrovoy obrabotke signalov. Zhurnal radioelektroniki, 1. Available at: http://jre.cplire.ru/jre/jan13/1/text.html
20. Bhatta, A., Mishra, A. K. (2017). GSM-based commsense system to measure and estimate environmental changes. IEEE Aerospace and Electronic Systems Magazine, 32 (2), 54–67. doi: https://doi.org/10.1109/maes.2017.150272
21. Neyt, X., Raout, J., Kubica, M., Kubica, V., Roques, S., Acheroy, M., Verly, J. G. (2006). Feasibility of STAP for Passive GSM-Based Radar. 2006 IEEE Conference on Radar. doi: https://doi.org/10.1109/radar.2006.1631853
22. Willis, N. J. (2004). Bistatic Radar. IET. doi: https://doi.org/10.1049/sbra003e
23. Lishchenko, V., Khudov, H., Tiutiunnyk, V., Kuprii, V., Zots, F., Misiyuk, G. (2019). The Method of Increasing the Detection Range of Unmanned Aerial Vehicles In Multiradar Systems Based on Surveillance Radars. 2019 IEEE 39th International Conference on Electronics and Nanotechnology (ELNANO). doi: https://doi.org/10.1109/elnano.2019.8783263
24. Ruban, I., Khudov, H., Lishchenko, V., Pukhovyi, O., Popov, S., Kolos, R. et al. (2020). Assessing the detection zones of radar stations with the additional use of radiation from external sources. Eastern-European Journal of Enterprise Technologies, 6 (9 (108)), 6–17. doi: https://doi.org/10.15587/1729-4061.2020.216118
25. Leshchenko, S., Kolesnik, O., Gricaenko, S., Burkovsky, S. (2017). Use of the ADS-B information in order to improve quality of the air space radar reconnaissance. Nauka i tekhnika Povitrianykh Syl Zbroinykh Syl Ukrainy, 3 (28), 69–75. Available at: http://nbuv.gov.ua/UJRN/Nitps_2017_3_11
26. Khudov, H., Diakonov, O., Kuchuk, N., Maliuha, V., Furmanov, K., Mylashenko, I. et al. (2021). Method for determining coordinates of airborne objects by radars with additional use of ADS-B receivers. Eastern-European Journal of Enterprise Technologies, 4 (9 (112)), 54–64. doi: https://doi.org/10.15587/1729-4061.2021.238407
27. LORAN-C. Available at: https://skybrary.aero/articles/loran-c
28. Multilateration (MLAT) Concept of Use. Available at: https://www.icao.int/APAC/Documents/edocs/mlat_concept.pdf
29. Neven, W. H., Quilter, T. J., Weedon, R., Hogendoorn, R. A. (2005). Wide Area Multilateration Report on EATMP TRS 131/04 Version 1.1. Available at: https://www.eurocontrol.int/sites/default/files/2019-05/surveilllance-report-wide-area-multilateration-200508.pdf

30. Mantilla-Gaviria, I. A., Leonardi, M., Balbastre-Tejedor, J. V., de los Reyes, E. (2013). On the application of singular value decomposition and Tikhonov regularization to ill-posed problems in hyperbolic passive location. Mathematical and Computer Modelling, 57 (7-8), 1999–2008. doi: https://doi.org/10.1016/j.mcm.2012.03.004
31. Schau, H., Robinson, A. (1987). Passive source localization employing intersecting spherical surfaces from time-of-arrival differences. IEEE Transactions on Acoustics, Speech, and Signal Processing, 35 (8), 1223–1225. doi: https://doi.org/10.1109/tassp.1987.1165266
32. Khudov, H., Mynko, P., Ikhsanov, S., Diakonov, O., Kovalenko, O., Solomonenko, Y. et al. (2021). Development a method for determining the coordinates of air objects by radars with the additional use of multilateration technology. Eastern-European Journal of Enterprise Technologies, 5 (9 (113)), 6–16. doi: https://doi.org/10.15587/1729-4061.2021.242935
33. Khudov, H., Yarosh, S., Droban, O., Lavrut, O., Hulak, Y., Porokhnia, I. et al. (2021). Development of a direct penetrating signal compensator in a distributed reception channel of a surveillance radar. Eastern-European Journal of Enterprise Technologies, 2 (9 (110)), 16–26. doi: https://doi.org/10.15587/1729-4061.2021.228133
34. Oleksenko, O., Khudov, H., Petrenko, K., Horobets, Y., Kolianda, V., Kuchuk, N. et al. (2021). The Development of the Method of Radar Observation System Construction of the Airspace on the Basis of Genetic Algorithm. International Journal of Emerging Technology and Advanced Engineering, 11 (8), 23–30. doi: https://doi.org/10.46338/ijetae0821_04
35. Ryu, H., Wee, I., Kim, T., Shim, D. H. (2020). Heterogeneous sensor fusion based omnidirectional object detection. 2020 20th International Conference on Control, Automation and Systems (ICCAS). doi: https://doi.org/10.23919/iccas50221.2020.9268431
36. Salman, S., Mir, J., Farooq, M. T., Malik, A. N., Haleemdeen, R. (2021). Machine Learning Inspired Efficient Audio Drone Detection using Acoustic Features. 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST). doi: https://doi.org/10.1109/ibcast51254.2021.9393232
37. SHAHED-136 Loitering munition / Kamikaze-Suicide drone – Iran (2023). Available at: https://www.armyrecognition.com/iran_unmanned_ground_aerial_vehicles_systems/shahed-136_loitering_munition_kamikaze-suicide_drone_iran_data.html#google_vignette
38. How drones are conquering the battlefield in Ukraine's war (2023). Available at: https://www.euronews.com/2023/06/06/how-drones-are-conquering-the-battlefield-in-ukraines-war
39. Space, the unseen frontier in the war in Ukraine (2022). BBC News. Available at: https://www.bbc.com/news/technology-63109532
40. NASAMS Air Defence System. Available at: https://www.kongsberg.com/kda/what-we-do/defence-and-security/integrated-air-and-missile-defence/nasams-air-defence-system/
41. Fedorov, A., Holovniak, D., Khudov, H., Misiyuk, G. (2019). Method of Radar Adjustment with Automatic Dependent Surveillance Technology Use. 2019 IEEE International Scientific-Practical Conference Problems of Infocommunications, Science and Technology (PIC S&T). doi: https://doi.org/10.1109/picst47496.2019.9061245
42. Byrne, J., Watling, J., Bronk, J., Somerville, G., Byrne, J., Crawford, J., Baker, J. (2022). The Orlan complex. Tracking the supply chains of Russia's most successful UAV. Royal United Services Institute for Defence and Security Studies. Available at: https://static.rusi.org/SR-Orlan-complex-web-final.pdf
43. Swiss Components For Cars and Electric Bicycles Were Found in russian Orlan-10 UAVs and Missiles (2023). Available at: https://en.defence-ua.com/industries/swiss_components_for_cars_and_electric_bicycles_were_found_in_russian_orlan_10_uavs_and_missiles-6267.html
44. What is a Spectrogram? Available at: https://vibrationresearch.com/blog/what-is-a-spectrogram
45. What is a Spectrogram? Available at: https://pnsn.org/spectrograms/what-is-a-spectrogram
46. Eleron-3SV. Available at: https://robotrends.ru/robopedia/eleron-3sv
47. Saybel', A. G. (1958). Osnovy teorii tochnosti radiotekhnicheskikh metodov mestoopredeleniya. Moscow: Oborongiz, 55.
48. Khudov, H., Zvonko, A., Lisohorskyi, B., Solomonenko, Y., Mynko, P., Glukhov, S. et al. (2022). Development of a rangefinding method for determining the coordinates of targets by a network of radar stations in counter-battery warfare. EUREKA: Physics and Engineering, 3, 121–132. doi: https://doi.org/10.21303/2461-4262.2022.002380
49. Ruban, I., Khudov, H., Makoveichuk, O., Butko, I., Glukhov, S., Khizhnyak, I. et al. (2022). Application of the Particle Swarm Algorithm to the Task of Image Segmentation for Remote Sensing of the Earth. Lecture Notes in Networks and Systems, 573–585. doi: https://doi.org/10.1007/978-981-19-5845-8_40
50. Khudov, H., Makoveichuk, O., Khizhnyak, I., Oleksenko, O., Khazhanets, Y., Solomonenko, Y. et al. (2022). Devising a method for segmenting complex structured images acquired from space observation systems based on the particle swarm algorithm. Eastern-European Journal of Enterprise Technologies, 2 (9 (116)), 6–13. doi: https://doi.org/10.15587/1729-4061.2022.255203
51. AIRSPY. Available at: https://airspy.com
52. Apaydin, G., Sevgi, L. (2017). Radio Wave Propagation and Parabolic Equation Modeling. The Institute of Electrical and Electronics Engineers. doi: https://doi.org/10.1002/9781119432166
53. P-19MA. Available at: http://uoe.com.ua/products/en/?id=0&pid=catalogue&language=eng&catalogue_id=515&type=content
54. HackRF One SDR-transiver (1 MHts – 6 HHts) maksymalna komplektatsiya. Available at: https://radioscan.com.ua/ua/p1878031526-hackrf-one-sdr.html