Integrated complex for determining sources of radio radiation with protection of information transmission*

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Abstract
This new solution belongs to the field of electronic communications and radio engineering, in particular to methods of determining the location of radiation sources in a hostile environment. This solution can be used in navigation, direction finding, and location-finding installations while solving the problem of covert determining of the coordinates of radio emission sources. Increasing efficiency of the use of the integrated complex for determining the location of ground-based radio emission sources of special purpose in comparison with known solutions occurs due to the introduction into the portable multifunctional equipment of the ground segment additional elements, such as an intelligent sensor of the electromagnetic environment and an infrastructure management system for monitoring territories by groups of aircraft. These groups are made in the form of interconnected groups of UAVs, which constitute the second level of the flying segment. At the same time, mobile access points and interconnected groups of main UAVs constitute the first level of the flying segment that relays received/transmitted data to the mobile communication base station. The presented solution ensures increased performance efficiency of the infrastructure of the integrated complex for determining the location of special-purpose ground radio radiation sources in the conditions in which the enemy uses ground radiation sources with directional antennas and operates at low radiation power. The accuracy increase of positioning is achieved by jointly using the data of the arrays of primary measurements of the portable multifunctional means for determining the location of the ground radio radiation sources and measurements of groups of UAVs of the second level of the flying segment, which are themselves mobile access points. Analysis of the proposed complex showed that it has high potential in the hostile electronic warfare environment.

Keywords
hostile electronic warfare environment, UAVs, special-purpose radio emission sources, positioning systems.

1. Introduction

In the conditions of combat operations, the effectiveness of the use of existing ground mobile radio control equipment with a limited height of their antenna devices is significantly reduced, and, as a result, the traditional use of ground multi-position location systems becomes practically inoperable. This is because in the conditions of deploying "low-power" ground sources of radio radiation with directional antennas and with account of limited time of radio signal radiation, the probability of simultaneous electromagnetic availability of ground sources of radio radiation to several (at least two) reception points of multi-positional location systems becomes extremely low. In this regard, the development of methods for determining radiation sources using unmanned airborne vehicles is extremely important. This allows significantly increasing the coverage area in which detection and determination of the coordinates of the radio radiation sources is secured, as well as high potential for ensuring protection of information transmitted in a hostile electronic warfare environment.

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2. Analysis of publications by research topic

In the literature [1-5], some implementations of complexes for determining the location of ground-based radio sources are presented. The first example of implementation receives signals in a given frequency band thanks to a measuring device moving in space, as well as thanks to assessing the primary coordinate-information parameters of the detected signals, for which the levels of the estimated signals are used; simultaneous measurement and storage of secondary signal parameters is also provided. This solution allows one to reduce the time spent on determining the coordinates of the radio radiation sources in the conditions of limited overall dimensions of the antenna for direction finding.

The disadvantage of such a solution is the relatively low accuracy of determining the coordinates of the radio radiation sources. This is due to the fact that when measuring the parameters of the radio signal, its polarization parameters are not taken into account; therefore, to achieve acceptable accuracy in determining the coordinates, additional correction of the aircraft flight route is necessary, which requires prolonged electromagnetic contact with the radio radiation sources.

The second known complex determines the coordinates of a radio radiation source with the help of amplitude-phase direction finder fitted onboard of the aircraft; this device performs the following operations: receiving radio signals by the onboard antenna, frequency selection, determining bearings, registering and processing the received data. The coordinates of the radio radiation source are determined as the intersection point of at least two bearing lines. When implementing this method, it is possible to combine the process of determining the coordinates of the radio radiation source with other tasks of radio monitoring: parametric and semantic control of signals.

The disadvantage of this solution is the relatively low accuracy of determining the coordinates of the radio radiation sources. This is caused by the occurrence of errors associated with random fluctuation in the spatial position of the plane of the direction finding antenna during the flight of the aircraft. The magnitude of these errors can be accounted similar to the operational and systematic errors of the hardware used.

Also known is a complex for determining the coordinates of a radio radiation source during amplitude-phase direction finding performed by the installation fitted onboard of the aircraft. This procedure includes reception of radio signals by the onboard direction finding antenna, frequency selection, determination of bearing lines, registration and weight processing of the received data. Bearing lines are determined in the plane of the direction finding antenna. According to the results of weight processing, auxiliary planes are also formed.

The disadvantage of such a solution is the relatively low accuracy of determining the coordinates of the radio radiation source, since when measuring the parameters of the radio signal its polarization parameters are not taken into account. In addition, there is a need to use antenna systems with elements spaced apart in space, what in most cases cannot be implemented due to the limited dimensions of the aircraft.

Another implementation of the complex for determining the coordinates of the radio radiation sources, which includes a 3-dimential onboard direction finding antenna array, represents a set of two flat antenna arrays located in parallel or intersecting planes. Such a solution allows providing the possibility of increasing the accuracy of radio direction finding in the azimuthal and elevation angle planes. At the same time, the ground component includes helicopter control equipment and an on-board radio direction finder with control and display devices and containers for transporting the target load.

The disadvantage of this complex is the relatively low accuracy of determining the coordinates of the radio radiation sources. This is explained primarily by the occurrence of errors associated with random fluctuations in the spatial position of the plane of the direction finding antenna during the flight of the aircraft. In addition, the bulkiness of the antenna structures on helicopter-type aircraft causes low operational reliability of the complex.

There is also a portable multifunctional means of determining the location of the source of radio radiation of the ground segment, which contains a direction finding system: this system consists of an antenna system for radio monitoring and direction finding, a digital radio receiver, an analog-digital signal processing unit, a data transmission system and a cartography and navigation system.

The disadvantages of such an integrated complex for determining the location of the radio radiation sources are caused by the fact that its functionality significantly depends on the height of the antenna devices set up above the earth's surface. This affects the range and operation zone. The widespread use of jamming-protected ground radio equipment (that operates in different frequency ranges at reduced power and with the use of directional antennas) by the Russian military to control military units and equipment during combat operations, leads to a significant reduction in the probability of their timely detection and determination of location (spatial localization) by ground-based radio control equipment. In addition, in real terrain conditions, the operation zone and the effectiveness of the use of the existing ground-based mobile radio control equipment with a limited height of the antenna installation are significantly reduced. At the same time, analysis of the proposed complex showed that it has a high potential for protecting information transmitted in a hostile electronic warfare environment. This is especially relevant in view of software-defined radio (SDR) technologies, since SDR receivers create additional cybersecurity challenges for wireless systems and may be used for flexible signal monitoring, interception, and analysis [6].

3. Task and aim formulation

The purpose of this article is to develop an approach and an integrated method to ensure increased efficiency of the functioning of the infrastructure of the integrated complex for determining the location of ground-based radio radiation sources for special purposes in conditions where the enemy uses ground-based radiation sources with directional antennas operating at low powers.

4. Description of the proposed method and the installation

4.1. Technical aspects of the proposed solution

The proposed solution is based on the introduction of the ground segment of additional elements into the portable multifunctional facility for determining the location of the radio radiation sources, namely:

- an intelligent electromagnetic environment sensor, which is connected to the output of a personal computer and consists of an *N*-channel data acquisition and signal matching system;
- data acquisition system drivers;
- random access memory device;
- a signal processing device consisting of a statistical processor and a feedforward neural network;
- infrastructure management system for monitoring territories by groups of flying vehicles. In this case, the infrastructure for monitoring territories by groups of flying vehicles is made in the form of interconnected groups of UAVs, which constitute the second level of the flying segment and operate as mobile access points. The second part of the system are interconnected groups of main UAVs, which constitute the first level of the flying segment and relay received/transmitted data to the mobile communication base station. Such a mobile communication station operates in normal mode.

The proposed solution provides increased efficiency of the infrastructure of the integrated complex for determining the location of ground-based special-purpose radio radiation sources in conditions of the enemy's use of ground-based radiation sources with directional antennas operating at low power. This is achieved by jointly using the data of the primary measurement arrays of the portable multifunctional means of determining the location of the radio radiation source of the ground segment and the changes of the second-level UAV groups of the flying segment, which are mobile access points, allowing to increase the accuracy of positioning.

The key difference between the proposed solution and traditional modern solutions used in integrated systems for determining the location of special-purpose ground-based radio radiation sources is the use of UAV/drone swarms to raise sensors above the ground, which improves the efficiency of detection and control of radio emission sources. Drones allow sensors to be raised to a height without resorting to the deployment of heavy tower-type structures, the use of which is limited by the ease of their detection and mobility. The high speed of deployment of the proposed radio reconnaissance complexes will allow them to be used closer to the line of contact and will have better camouflage of the crews. In conditions where enemy sources use directional antennas and operate at low power, making their detection difficult, this becomes a great advantage because it will allow detecting the positions of enemy UAV crews during their direct operation.

The peculiarity of the proposed solution in the integrated complex for determining the location of ground-based radio radiation sources for special purposes is as follows:

Firstly, such a solution has a portable multifunctional means of determining the location of the source of radio radiation of the ground segment, containing a direction finding system consisting of:

- antenna system for radio monitoring and direction finding;
- digital radio receiver;
- analog-digital signal processing unit;
- data transmission system, which in turn consists of a radio modem and a radio modem antenna;
- cartography and navigation system, also consisting of a cartography and navigation device and a cartography and navigation antenna;
- personal computer;
- power systems.

Secondly, the following have been additionally introduced into the complex:

- an intelligent electromagnetic environment sensor, which is connected to the output of a personal computer and consists of an *N*-channel data acquisition and signal matching system;
- data acquisition system drivers;
- random access memory device;
- a signal processing device consisting of a statistical processor and a feedforward neural network;
- infrastructure management systems for monitoring territories by groups of flying vehicles.

Thirdly, the infrastructure for monitoring territories by groups of flying vehicles is made in the form of interconnected groups of UAVs, which constitute the second level of the flying segment and operate as mobile access points. The second part of the system are interconnected groups of main UAVs, which constitute the first level of the flying segment and relay received/transmitted data to the mobile communication base station. Such a mobile communication station operates in normal mode.

Fourthly, the infrastructure for monitoring territories by groups of flying segment UAVs is divided into two levels. The first level consists of the main UAVs, and the second level consists of the UAV members in each group (see Figure 1).

The integrated complex for determining the location of a radio radiation source (as a variant of the design) is shown in Figure 1. This complex contains a ground segment 1 which includes a ground portable multifunctional equipment 2 for determining the location of a radio radiation source of the ground segment, an intelligent sensor of the electromagnetic environment 3, a control system 4 of the infrastructure for monitoring territories by groups of aircraft, a command post 5 for controlling the complex, a remote base station 6, sources of radio radiation 7 and the airborne segment 8. The airborne segment includes an infrastructure 9 for monitoring territories by groups of aircraft of the airborne segment, which contains interconnected groups of main UAVs $10_{1 \dots n}$, an infrastructure 11 for monitoring territories by groups of aircraft of the airborne segment, which also contains interconnected separate groups $12_{1..n}$ of 3-5 aircraft.

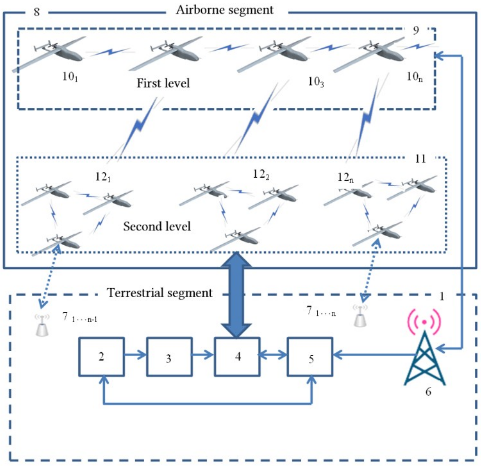

Figure 1: Integrated structure of an automated complex for determining the location of ground sources of radio radiation for solving tasks by special forces

Communication between UAV members in the first level group and between UAV members and the main UAV in the second level group is carried out on the basis of the IEEE 802.11p standard, which was developed for wireless information transmission between vehicles with support for self-organization. Communication between the main UAVs in different groups is carried out using IEEE 802.11p* technology in extended mode, which can provide data transmission at a distance of up to 740 m [7].

The technical result in an integrated complex for determining the location of ground sources of special-purpose radio radiation is to increase reliability and efficiency in conditions of modern military conflicts, where accuracy and efficiency play a critical role in the successful conduct of combat operations.

The specified result is achieved by the fact that the specified complex uses the infrastructure of an integrated solution based on a portable multifunctional equipment of determining the location of radio radiation sources of the ground segment, a network of UAVs of the flying segment, and infrastructure facilities of the existing mobile network.

At the same time, UAVs can provide a wider coverage of the working area and the ability to effectively detect enemy sources of radio radiation in real terrain conditions. It is also envisaged to combine UAVs equipped with sensors into a single network to obtain accurate data by information integration. This method allows several UAVs to interact, what simultaneously raise sensors above the ground; this creates the possibility of determining the exact location of radio radiation sources by analyzing signals from different points.

The proposed solution is designed to expand the capabilities of automated combat systems, improving detection, control and efficiency in wartime conditions. Further development of such innovations can increase overall efficiency and military potential, ensuring security and protecting national interests.

4.2. Construction of the integrated complex for determining the location of ground sources of radio radiation based on special-purpose UAVs

The essence of the proposed solution implemented in the integrated complex for determining the location of special-purpose terrestrial radio emission sources is explained in the figures shown above and below. Figure 1 illustrates the integrated structure of the automated complex for determining the location of ground sources of radio radiation for solving tasks by special forces, while Figure 2 shows the block diagram of a portable multifunctional equipment for determining the location of a ground segment radio radiation sources. In Figure 3, one can see the block diagram of an intelligent sensor based on programmable logic devices for assessing the electromagnetic environment in real time, while Figure 4 demonstrates the functional scheme of integrating measurements by a portable multifunctional device for determining the location of a ground segment radio radiation sources and the infrastructure for monitoring territories by groups of airborne vehicles of the airborne segment. In Figure 5 one can observe the graphs of the probability density dependence and the histogram of the location finding error on receiving 40 signals.

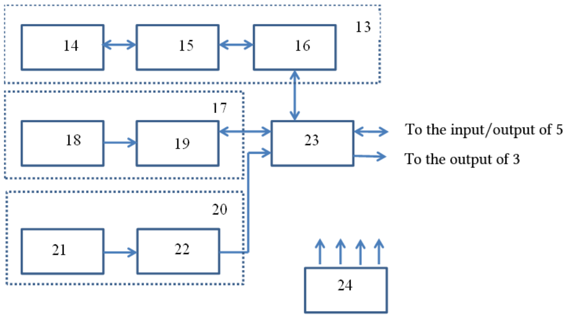

Figure 2: Structural diagram of the portable multifunctional equipment for determining the location of a radio radiation source of the ground segment

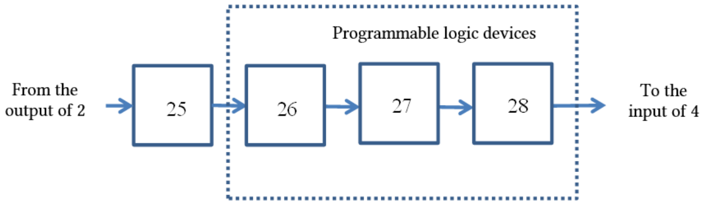

Figure 3: Block diagram of the intelligent sensor based on programmable logic devices for assessing the electromagnetic environment in real time

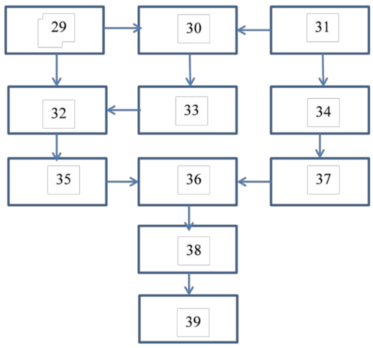

Figure 4: Functional scheme of integrating measurements by a portable multifunctional equipment of determining the location of a radio radiation source of the ground segment and the infrastructure of monitoring territories by groups of flying vehicles of the airborne segment

4.3. Method for determining the location of ground sources of radio radiation based on special-purpose UAVs

In the integrated complex, the locations of ground-based sources of special-purpose radio radiation are determined as described below and illustrated in Figure 1 and Figure 4, on which are marked:

1 — ground segment,

2 — ground portable multifunctional equipment of determining the location of the sources of radio radiation of the ground segment,

3 — intelligent sensor of the electromagnetic environment,

4 — infrastructure management system for monitoring territories by groups of aircraft,

5 — command post for controlling the complex,

6 — remote base station of mobile communications,
7 — sources of radio radiation,
8 — airborne segment,
9 — infrastructure for monitoring territories by groups of aircraft of the airborne segment of the first level,
10 — 1...n-groups of main UAVs of the first level,
11 — infrastructure for monitoring territories by groups of aircraft of the airborne segment of the second level,
12 — 1..n-separate groups of 3-5 aircraft of the second level.
In Figure 4 one can see the following elements:
29 — measured RSSI values by a ground-based portable multifunctional equipment of determining the location of the source of radio radiation of the ground segment,
30 — fixed time counts,
31 — measured RSSI values from UAV groups by the infrastructure of monitoring territories by groups of flying vehicles of the airborne segment,
32 — nearest neighbor method,
33 — radio map database,
34 — data transmission to the command post,
35 — coordinates of radio electronic means (REM) on the radio map,
36 — Kalman filter,
37 — REM coordinates based on UAV group data,
38 — determining the location of REM,
39 — calculation of the mean square error.

The installation operates in the following way. At the first stage, when collecting primary data, a database (DB) of the RSSI radio map is formed (refer to unit 33 in Figure 4) based on the database of measurements of the location of radio radiation sources obtained by the ground-based portable multifunctional device 2 (see Figure 1) of the ground segment (see unit 29 in Figure 4) and the group of UAVs 11 of the second level of the airborne segment (see Figure 1 and unit 31 in Figure 4). The measurements are collected into a DB table containing data on RSSI levels and time reports. The results of the first stage are a DB of the radio map (see unit 33 in Figure 4), which contains a set of RSSI measurements of the portable multifunctional device 2 (see Figure 1) of the ground segment and the group of UAVs of the second level 11 of the air segment for the corresponding coordinates.

In this case, the infrastructure for monitoring territories by groups of flying vehicles of the airborne segment is made in the form of interconnected groups of UAVs, which constitute the second level 11 of the airborne segment and are mobile access points for radiation sources 7, marked as 1...n (see Figure 1), and interconnected groups of main UAVs 10 marked as 1... n, which constitute the first level 9 of the flying segment and relay received/transmitted data to the mobile communication base station 6 (see Figure 1), which operates in the ordinary mode.

The location of the radio radiation sources of the ground segment by the portable multifunctional device 2 (see Figure 1) is carried out by the classical triangulation method [8]. This process is explained as follows below and is illustrated in Figure 2, where elements are marked as:

13 — direction finding system,
14 — antenna system for radio monitoring and direction finding,
15 — digital radio receiving device,
16 — analog-digital signal processing unit,
17 — data transmission system,
18 — radio modem antenna,

19 — radio modem,

20 — cartography and navigation system,

21 — antenna of the cartography and navigation device,

22 — cartography and navigation device,

23 — personal computer,

24 — power supply system.

The obtained coordinate determination data (see unit 35 in Figure 4) are used to form a flight task for UAV groups 11 of the second level of the airborne segment and are simultaneously used in the integration of measurements by a portable multifunctional equipment of determining the location of the radio radiation source of the ground segment and the infrastructure for monitoring territories by groups of second-level aircraft 11 of the airborne segment (see Figure 1).

For the operational assessment of changes in the dynamic parameters of the electromagnetic environment in real time of the portable multifunctional equipment 2, an intelligent sensor 3 is used (see Figure 1).

The structure of the intelligent sensor 3 is shown in Figure 3, where

25 — *N*-channel data acquisition and signal matching system,

26 — data acquisition system driver,

27 — random access memory device,

28 — signal processing device, consisting of a statistical processor and a feedforward neural network.

N-channel data acquisition and signal matching system 25 receives signals from the output of a personal computer 23 (see Figure 2). Signal processing is performed using a processor implemented on the basis of PLD blocks 26-28 (see Figure 3). Information exchange is carried out via the RS232 interface built into the PLD. Measurement data are sent to the connected control system 4 of the infrastructure for monitoring territories by groups of aircraft 11 (see Figure 1).

In addition, the RSSI values that are measured in this way are used when integrating measurements by the portable multifunctional installation for determining the location of a radio radiation source of the ground segment and by the infrastructure for monitoring territories by groups of aircraft of the second level 11 of the flying segment (see Figure 4). This approach enables to secure an increase in the insufficient frequency of RSSI measurements and, accordingly, an increase in the positioning accuracy of radiation sources $7_{1..n}$ (see Figure 1).

The second-level UAV group 11 (see Figure 1), first performs primary processing of information on board the UAV. After that, the data on detected sources of radio radiation is relayed to the mobile communication base station 6 through the groups of main UAVs 9 (see Figure 1), which make up the first level of the airborne segment. In this case, the base station operates in the normal mode.

Second, data on high-speed communication channels is transmitted to the ground command post 5 of the complex control, where secondary processing and display of data on the revealed radio-electronic situation against the background of an electronic map of the area are carried out (block 20, Figure 2). To transmit a larger amount of data from the UAV (data on sources of radio radiation detected in a wide frequency range), terahertz data transmission equipment is used. For this purpose, the first and second level UAV groups additionally includes a transceiver module (radar module TRX_024_06) of the terahertz range [8] in the form of integrated circuits containing a complete transceiver with a built-in strip antenna array, designed to measure distance and RSSI.

At the second stage, the DB measurement data sets are compared with the RSSI measurements of the ground portable multifunctional equipment 2 for determining the location of the radio radiation sources of the ground segment and the second level UAV group 11, the corresponding coordinates are selected using the nearest neighbor method (see block 32 in Figure 4).

The intermediate results of the coordinate estimation by each method are separately integrated by the Kalman filter (see block 36 in Figure 4) to increase the positioning accuracy and compensate for random emissions.

4.4. Radiation object location model

The process of determining the location of a radiation object by a group of second-level UAVs is explained as follows.

Assuming that the radiation source is on the ground (z_o=0), it is necessary to find the coordinate of the radiation source location (x_i,y_i,0) and the *i*-th position of the group of second-level UAVs (x_i,y_i,z_i) when receiving a signal from the radiation source. If the group of second-level UAVs receives *m* signals from the radiation source, the coordinates of the location point must satisfy equation (1):

$$\begin{cases} (x_1-x_0)^2+(y_1-y_0)^2+(z_1)^2=(d_1)^2 \\ \dots\dots \\ (x_i-x_0)^2+(y_i-y_0)^2+(z_i)^2=(d_i)^2 \\ \dots\dots \\ (x_m-x_0)^2+(y_m-y_0)^2+(z_m)^2=(d_m)^2 \end{cases} \quad (1)$$

where d_i is the distance from the second-level UAV group to the radiation source.

In a wireless radio channel, signal power loss during propagation through the medium are estimated taking into account radio wave propagation models. Thus, the power of the received signal is less than the power of the transmitted one. To predict the difference between the transmitted and received signals, the power of each received radio signal is measured using the Received Signal Strength Indicator (RSSI) [9].

The distance based on RSSI indicators is usually calculated based on the model of logarithmic signal power loss during propagation in the medium:

$$RSSI=A-10*n*\log(d/d_0)+X_Q, \quad (2)$$

where *d* is the distance from the device to the transmitter (*m*); *A* is the signal power of the device measured at a unit distance d_0 from the device (dBm); *n* is the signal power loss coefficient when propagating in the environment, the indicator is associated with a specific wireless communication technology; X_σ is a Gaussian distribution of a random variable with a zero mean and a variance of σ^2.

Since the loss of signal power when propagating in the environment depends on the environment, to increase the positioning accuracy in the proposed technical solution, it is necessary to estimate the parameters *A* and *n* before deploying the location operation.

Therefore, in each specific operation to determine the location of the radiation source, the second-level UAV group performs a preliminary calibration, i.e. the RSSI indicator is calculated taking into account the distance between the second-level UAV group and the starting point; the measurement is performed several times.

Then, a nonlinear least squares method is used to find the optimal parameters *A*, *n*. With *m* measurements, these parameters are defined as:

$$(A,n)=argmin\left(\sum_{i=1}^{m}10^{\frac{A-RSSI}{10n}}-d_i\right)^2. \quad (3)$$

After determining the distance to the radiation source, it is necessary to calculate the coordinates of this radiation source.

This process is performed as shown below. Suppose that the position of the radiation source is $p(x_i,y_i,0)$, and a group of second-level UAVs receives a signal from the radiation source at position $p_i(x_i,y_i,z_i)$. The distance between these two points is calculated taking into account the measurement error established during calibration. With each received signal from the radiation source, the distance from it to the group of second-level UAVs is:

$$d(p_i, p_0)=\sqrt{(x_i-x_0)^2+(y_{(i)}-y_0)^2+(z_0)^2}+\varepsilon. \tag{4}$$

Thus, the number of signals received and the measurement error ε affect the accuracy of the positioning process. The position $p_k(x_k, y_k)$ is determined by minimizing expression (5):

$$arg\,min\,\Sigma_{(i=1)}^{m}\left(\sqrt{(x_i-x_k)^2+(y_{(i)}-y_k)^2+(z_i)^2}\right)-d\left(\left(p_{(i,)}\,p_k\right)\right) \tag{5}$$

where m is the number of signals received from an unauthorized source.

As a result of minimization, it becomes possible to calculate the coordinates of the radiation source and the errors (see blocks 38 and 39 in Figure 4).

Thus, to assess the possibility of determining the location based on the received signal, the developed model takes into account the number of received signals and measurement errors. The simulation results show that the location error increases when the distance measurement error increases (see Figure 5).

Considering the obtained dependencies, the accuracy of location determination can be achieved by improving the quality of distance measurement and ensuring the detection of a larger number of signals [10–16]. The reliability of such positioning and measurement integration also depends on the stability of information transmission channels, since channel failures directly affect the timeliness and correctness of decision-making in complex information systems [15].

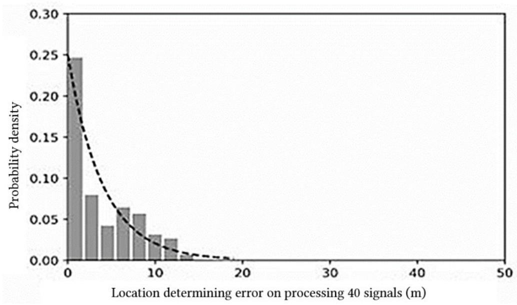

Figure 5: Probability density and histogram of location error on receiving 40 signals.

5. Analysis of the proposed method and the complex from the point of view of information transmission security

Modern UAVs are actively integrated into military, special and civil telecommunication networks, providing real-time data collection, processing and transmission. With the increasing intensity of UAV use in network-centric architectures, there is an urgent need for a comprehensive analysis of the security of information transmission processes, especially at the physical level, where fundamental restrictions on the stability and reliability of communications are laid. In the conditions of a dynamic radio-electronic environment, multi-beam signal propagation and active enemy influences, the problem of protecting control and telemetry channels from interception, intentional interference and unauthorized interference arises. The physical level, being the basis of the entire network architecture, determines the level of trust in the system as a whole. The effectiveness of the application of adaptive modulation, coding, spatial-temporal algorithms and spectral monitoring methods directly affects the probability of detection, resistance to denial of service (DoS) attacks and maintaining the confidentiality of information flows. An integrated approach that combines physical protection mechanisms with higher levels of protocols and elements of artificial intelligence for predicting and countering threats is also important. Similar cooperative sensing principles are used in V2X-based UAV detection, where distributed infrastructure elements jointly process radio-frequency observations to improve detection coverage and resilience without disrupting communication functions [17]. Methods for detecting radio signals by estimating their parameters are also relevant for such integrated monitoring systems, especially when the system must operate under complex propagation and electronic warfare conditions [18].

Thus, the study of information transmission security problems and the physical layer in integrated UAV complexes has scientific and applied value, as it is aimed at developing methods for increasing the stability of communication channels and ensuring guaranteed quality of services in critical application conditions.

The developed method and complex for ensuring the security of information transmission using UAVs are focused on increasing protection against physical layer threats and reducing the probability of signal interception. Physical layer problems and technical solutions are given in Table. 1.

Table 1
Problems of physical and technical levels and their solutions for ensuring the security of information transmission using UAVs

Physical level problem	Technical solution
Radio electronic suppression (jamming, blocking)	Dynamic frequency hopping (FHSS) Use of wideband cognitive radio systems Adaptive antennas with spatial signal selection (LCMV, MVDR, null-steering)
Signal imitation (spoofing)	Signal authentication (digital watermarks in phase-time parameters) Correlation verification of data from multiple UAVs Machine learning for detecting anomalous signals
Interception of UAV control channels	Cryptographic protection of the physical layer (encryption at the modulation level) Duplicated control channels (direct + relay via the main UAV) Autonomous self-return modes in case of loss of communication
Unmasking signs of UAV (radar, acoustic)	Use of stealth coatings and radio-transparent materials Low-noise electric motors and acoustic dampers Use of simulated UAV decoys Low-noise electric motors and acoustic dampers Use of simulated UAV decoys
Overload of communication channels	Multi-agent routing with QoS priorities Adaptive real-time data compression Local signal processing at the second level of the UAV with transmission of only generalized results
Detection of low-power and directed enemy sources of radio radiation	Cooperative signal processing from ground segment sensors and UAV Interferometric antennas for accurate direction finding at low SNR Coherent accumulation and compressed sensing algorithms

The proposed method and the designed complex create multi-level protection at the physical level, but require additional integration of cryptographic and organizational measures to fully guarantee the security of information transmission.

The impact of technical countermeasures on the possible threats" is given in Table 2.

To implement the proposed measures, the architectural principles of the system security are as follows:

- Layering: physical LPI/LPD + MAC access control + cryptography (end-to-end) + anomaly monitoring.
- Redundancy: duplicate C2 (frequency/space/protocol), independent time (GNSS+PTP-Grandmaster on UAV-1).

- Exposure minimization: narrow beams, adaptive power control, “silent windows”.
- Trusted hardware base: key protection in TPM/PUF; on-board memory protection (AES-XTS, secure erase, tamper-evident).
- Digital supply chains: signed OTA updates, SBOM, firmware verification before flight.

Table 2
Impact of technical countermeasures on threats

Threat	Key metrics	Countermeasures
Jamming	Gp, SINR, J/Sth	FHSS/DSSS, reactive reconfiguration, LCMV/null-steering, spatial diversity, LDPC/Polar codes
RF/GNSS spoofing KL divergence	GLRT-residuals TDOA/FDOA PHY-watermarks, RF-fingerprinting, multi-sensor verification, anti-spoof GNSS	
C2 interception	Cs, BER under interception	PHY encryption + spreading, narrow beam links, PHY keys from the channel, anti-replay)
UAV unmasking	RCS/SPL/emissions	Cryptographic protection of the physical layer (encryption at the modulation level)
Network Congestion	Z-delay, losses, goodput	In-network processing, R-D compression, QoS priorities, opportunistic backhaul
Low power radio radiation sources	CRLB AOA, GDOP, Pd/Pfa	Interferometry, coherent accumulation, compressed sensing, trajectory planning

The following attack decision-making algorithm (runbook, PHY-level) can be implemented:

1. Detection: BER jump, SINR drop, energy gain in extraneous Doppler components → “EW” trigger.
2. Adaptation: FH pattern with different pseudo-sequence; beam narrowing; duty cycle reduction; switch to backup C2.
3. Source validation: GLRT consistency (TDOA/FDOA/AOA), watermark check; if not — “suspicion of spoofing”.
4. Cooperation: request additional measurements from 2-3 UAV-2; increase coherent accumulation time.
5. Traffic migration: only metadata/features; raw IQ — on request.
6. Logs and telemetry: frame hash chains (integrity), preservation for post-mortem.

The following recommendations for improving security can be formulated:

- Layering: physical LPI/LPD + MAC access control + cryptography (end-to-end) + anomaly monitoring.
- Combining physical protection with cryptographic encryption and authentication methods.
- Using multi-level attack detection schemes at the physical level (spoofing, jamming, interception).
- Development of mechanisms for verifying the authenticity of spectral information for cognitive radio.
- Implementation of backup communication scenarios (e.g. laser or optical channels) in case of radio spectrum blocking.

6. Directions of further scientific work

Further research can be concentrated on the development of a set of positioning models using UAVs, which allow visualizing the process of processing primary measurements and estimating the coordinates of radio radiation sources for various topologies of stationary receiving points in the ground segment and the trajectories of the receiving points on board the UAV in the air segment.

7. Conclusions

Increasing effectiveness of the use of the integrated complex for determining the location of ground sources of special-purpose radio radiation in comparison with existing approaches consists in the additional introduction of supplementary elements into the portable multifunctional equipment for determining the location of the ground segment of the sources of radio radiation. Those elements are the following: an intelligent sensor (sensor) of the electromagnetic environment and the management system for the infrastructure for monitoring territories by groups of aircraft. This infrastructure for monitoring territories by groups of aircraft is made in the form of interconnected groups of UAVs, which constitute the second level of the flying segment and are mobile access points. The second element of this infrastructure are interconnected groups of main UAVs, which constitute the first level of the flying segment and relay received/transmitted data to the mobile communication base station. This base station operates in the normal mode, ensuring increased reliability and efficiency in conditions of modern military conflicts, where accuracy and efficiency play a critical role in the successful conduct of combat operations.

The specified result is achieved by the fact that the proposed approach uses an integrated solution based on a portable multifunctional equipment of determining the location of the sources of radio radiation of the ground segment, the UAV network of the airborne segment as well as the infrastructure of the existing mobile network. At the same time, UAVs can provide a wider coverage of the working area and the ability to effectively detect enemy sources of radio radiation in real terrain conditions.

The analysis of the proposed complex showed that it has high potential in the hostile EW environment under the condition of strict PHY-level engineering: spectral and spatial aggregation of stability (FHSS/DSSS + MIMO/null-steering), multi-position validation of measurements (TDOA/FDOA/AOA), PHY-authentication/watermarks, LPD/LPD-tactics and in-network processing.

Declaration on Generative AI

While preparing this work, the authors used the AI programs Grammarly Pro to correct text grammar and Strike Plagiarism to search for possible plagiarism. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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