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ASSESSMENT of DEAD ZONE OF JOINTLY OPERATING RADARS

Abstract. Research relevance. With the emergence of unmanned aerial vehicles, the assignments of combating them have also become significantly more relevant. Today, operational countermeasures against UAVs are of great importance. Modern UAVs are capable not only of conducting video reconnaissance in a certain area, but also of observing a specific object for a long time and striking it. After detecting and identifying UAVs by RLS, it is necessary to take measures to neutralize them. In the paper, a mathematical model of the evaluation of the dead zone of RLS working together for the effective detection of unmanned aerial vehicles was established and a comparison of the dead zones was made on concrete examples. The **purpose** of the research work is to solve the problem of effective placement of jointly operating RLS by mathematical methods for nonobserved remaining part of them had minimal volume and to select the necessary placement scheme. The following **tasks** are solved in the article: analysis of the characteristics of the radar field; development of a mathematical model for evaluating the dead zone of joint radar stations; evaluation of some accommodation options. The following **research methods** are used to solve the issues: theoretical analysis, mathematical modeling, comparative analysis. The following **results** were obtained: it was observed that the dead zone was reduced by 1.6 times in the four-station square arrangement scheme, and by 1.3 times in the three-station triangular arrangement scheme. **Conclusions:** From the comparison of the obtained numbers, it can be concluded that the creation of a radiolocation area by placing RLSs on the vertices of equilateral triangles (in the form of a checkerboard) is more economically profitable, as it requires fewer stations.

Keywords: unmanned aerial vehicles, dead zone, radiolocation area, effective reflection area, radiolocation station.

Introduction

Analysis of the 2020 Patriotic War and the ongoing Russian-Ukrainian war, as well as recent occuring local wars and conflicts, shows that the detection of UAVs is one of the main issues for combating them [1-4]. For a more effective fight against UAVs, it is important factor to quickly detect them both at long distances and in the dead zone [5-7].

Modern local conflicts, where high-precision weapons and military equipment are more involved, impose new requirements for conducting combat operations. UAVs, in turn, at the present stage of the development of science and technology are being developed more and more, creating many difficulties for air defense systems. These difficulties are related to the following factors:

- small effective reflection area, i.e. small radiolocation visibility (effective reflection area 0,01-0,001 m^2), visual detection less than 100 m (in ideal weather conditions), the hearing of the sound is 15-50 m, (0,5 Wt/rad) olması;
- low flight speeds (10-30 m/sec), wide diapason of movement speeds, performance of flights at low and minimum altitudes using the terrain;
- to have the little time for obtaining information about the type of object according to its spatial (geometric) characteristics and making a timely decision;
- in the characteristics of the RLS, there are so-called "dead zone" with a radius of tens of kilometers, where it is impossible to detect and track aerial objects [8-10].

In order to increase the probability of detecting targets (increasing the effectiveness), the minimum size (volume) of the dead zone is one of the main conditions.

This task was considered in [5]. In this work it is shown that one of the problems of modern radio engineering troops is the impossibility of detecting low-altitude small-sized air objects over the position of a radio engineering unit. This is due to the presence of a dead zone (funnel) of surveillance radar detection zones. The solution to this problem can be the use of mobile small-sized vertical sounding radars.

In [11] the issues of assessing the visibility zone of radar station in a noise-free environment and under the influence of interference are considered. An algorithm for complex estimation of radar parameters is proposed. The relation of the tactical characteristics of the radar with its technical characteristics and the targets is considered.

In [12] the new generalized indicator of the technical and economic analysis and a choice of options of creation of land radio engineering means of a special purpose on the basis of convolution of indicators tactical and technical (power) and operational technical characteristics is offered.

In [13] the problem of creating a continuous field in the army's operational range by ground-based radars with a lower boundary height of 300-500 meters in front of the forward edge and in tactical depth is considered. At the same time, the height of the upper boundary of the radar field, as a rule, is not set and is determined by the capabilities of the radar, which are in service with air defense units.

However, in the above works, the method for selecting radar layouts to reduce radar dead zones is not considered. Therefore, the problem of assessing the dead zones of jointly operating radars is relevant.

The article presents a mathematical model for estimating the dead zone of joint radar stations for effective detection of unmanned aerial vehicles and compares the dead zones on specific examples. The purpose of the study is to solve the problem of effective placement of RLSs by mathematical methods and choose the necessary placement scheme so that the unobserved part (dead zone) of the joint radar stations is minimal (maximum visibility).

Radar area and scheme of the dead zone

A dead zone (DZ) is a section of space above a RLS that is outside the radar's observations and in which the RLS cannot detect air targets (Fig. 1). The presence of a dead gap is determined by the appropriate selection of the orientation diagram in the verical plane of the radar station, which depends on the relief of the area in the area of influence of the station, the nature of the position, the height of the antenna and the technical parameters of the RLS. It is impossible to detect and track aerial targets in a dead zone [14].

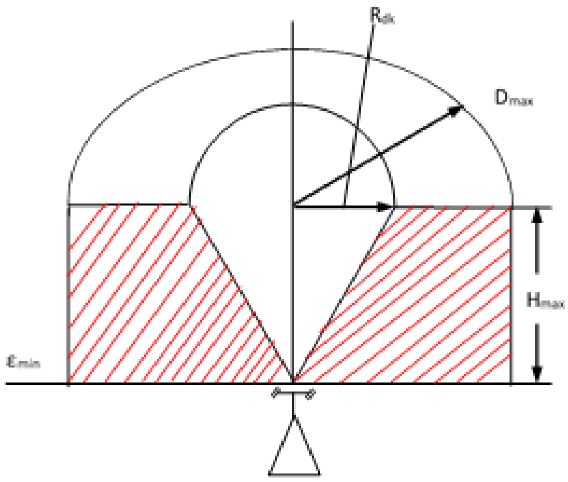

Fig. 1

The area of view of radiolocation stations is determined by the design of the RLS antenna and its operating characteristics (wavelength, transmission power, and other parameters).

When creating a grouping of RLS for the detection of UAVs, the detection zones of radiolocation stations have the following important features that must be taken into account:

1. The boundary of the sighting zones of the radiolocation stations indicates the diapason of target detection depending on the target's flight height. The earth's surface significantly affects the formation of the direction diagram of radiolocation stations for meter and decimeter ranges. This means that the terrain will have a significant effect on the area of view of the radiolocation station. As a result, the detection ranges of the same type of air targets at the same altitude can be different in different directions.

2. Radiolocation stations are used to conduct reconnaissance of the air enemy in a circular search mode. The detection of air attack vehicles by RLS in the vertical plane is limited, which leads to the presence of so-called "dead zones" in the field of vision, where it is impossible for RLS to observe air targets.

The following requirements must be met when creating a grouping of RLSs for the detection of UAVs:

- in the most probable flight directions of the enemy's air attacks (in front of the front line) the far border of the detection zone should be set;
- the continuous radiolocation area must cover the entire area at the possible altitudes of the enemy's air attack vehicles flight, and the probability of detecting targets at any point of the radiolocation area must be at least 0.75;
- radiolocation field should have high durability;
-the radiolocation area should be created with the maximum saving on the number of RLSs.

Choosing the optimal value of the height of the lower border of the radiolocation area is one of the most important conditions for fulfilling the above requirements. Two neighboring stations provide a continuous radiolocation area only starting from a certain minimum height (H_{min}) and the smaller the distance between the RLSs, the smaller the lower bound of the continuous field (Fig. 2).

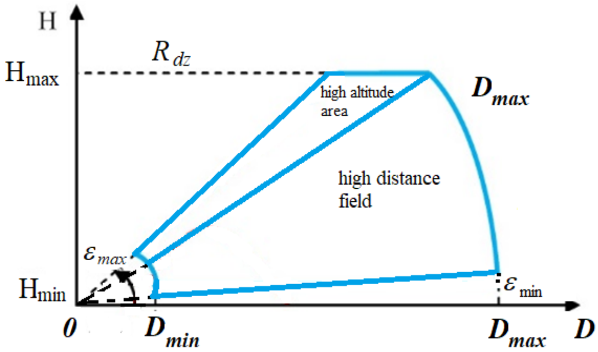

Fig. 2

The smaller the height of the lower boundary of the radiolocation area, the closer the RLSs need to be placed, so more RLSs will be required to create a continuous radiolocation area (this is contrary to the above requirements). In addition, the lower the altitude of the lower boundary of the radiolocation area, the smaller the far boundary of the detection zone at that altitude [15].

Currently, the state and trends of the development of UAV require the creation of a radar site at a height of several tens of meters (50-60 m). In this regard, a large number of RLS will be required to create a radiolocation area with this height of low boundary. Calculations show that when the height of the lower boundary of the radiolocation area is reduced from 500 m to 300 m, the need for the number of RLSs increases by 2.2 times, and when it is reduced from 500 m to 100 m, it increases by 7 times.

As a rule, the height of the upper border of the radiolocation area is not determined, they are determined by the capabilities of the radiolocation stations [13].

Problem statement

The development of a general methodology for calculating the values of the intervals and distances between RLSs, which contain different types of radiolocation stations in the radiotechnical grouping, and the nature of the terrain does not significantly affect the radar area, constitutes the issue. Taking this into account, it is required to create a radiolocation area with the height of the lower border of the radiolocation area "H_{min}".

Thus, depending on the location of radiolocation stations in the area, the dead zone (zone outside of observation) will be different. The purpose of the research is to investigate the issue of evaluating the dead zone (zone outside of observation) depending on the place of radiolocation stations in the area.

Mathematical formulation and solution of the problem

We will assume that radiolocation stations operate in a fairly limited area, so we can ignore the curvature of the Earth's surface when describing the location area. To give the place of the radar stations relative to each other in the area, let us introduce the $Oxyz$ positively oriented rectangular coordinate system with related to the ground [16, p.73], traditionally, the Oz axis can be considered perpendicular to the Earth's surface, pointing vertically upwards. Let's assume that it is planned to place *k* number of radiolocation stations in the area.

Let us denote the coordinates of the locations of the radiolocation stations relative to the $Oxyz$ system through $\{(x_i, y_i, z_i),\ i = 1, 2, \ldots, k\}$. According to the requirement of the problem, the distance between radiolocation stations is required to be at minimal l_0, in other words, the following inequalities must be satisfied relative the coordinates of the points:

$$\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2 + \left(z_j - z_i\right)^2 \geq l_0^2, \quad i, j = 1, 2, \ldots, k, \quad i \neq j. \tag{1}$$

As mentioned above, in general, the characteristic indicators of radiolocation stations may differ from each other. Let us denote the target sighting distance of the i -th radiolocation station as d_i, and the characteristic angle of its unobserved sector as α_i $(i = 1, 2, \ldots, k)$.

In general, a dead conyon (zone beyond observation) is a three-dimensional space figure, we will consider that the evaluation of these figures can be done based on their volume.

It is clear that geometrically the dead zone (zone outside of observation) of the i-th radiolocation station taken separately can be described as a truncated cone, let us denote this cone as K_i. Then the height of the cone K_i is calculated by the formula $h_i = d_i \operatorname{ctg}\frac{\alpha_i}{2}$. If take into account that the coordinates of the radar station are (x_i, y_i, z_i), the cuted cone K_i can be expressed as

$$K_i = \left\{ \begin{matrix} (x, y, z) |\ x^2 + y^2 \leq \left[\frac{d_i}{h_i}(z - z_i)\right]^2, \\ 0 \leq z - z_i \leq h_i \end{matrix} \right\},$$

its volume will calculated by the following formula [17, p. 347]:

$$V_{0i} = \iiint_{(x,y,z)\in K_i} dxdydz = = \pi \frac{d_i^2}{h_i^2} \int_{z_i}^{z_i + h_i} (z - z_i)^2 dz. \tag{2}$$

However, it is clear that to estimate the dead zone (zone excluded from observation) of radiolocation stations operating together the formal sum of the quantities determined by the formulas (2) cannot be taken, this is due to the fact that they have intersecting parts.

To solve the problem, it is necessary to reduce the volume of each radar station's dead zone (zone outside of observation) by the volume of the part that other radar stations can see this zone. Let's calculate this volume for the i- th radiolocation station. For other radiolocation stations, the dead zone (zone outside of observation) is expressed as $\bigcup_{j\neq i} K_j$. Then it can be written the following formula for the sought volume:

$$V_i = \iiint_{(x,y,z)\in K_i \setminus \bigcup_{j\neq i} K_j} dxdydz. \tag{3}$$

Considering that the sets $K_i \setminus \bigcup_{j\neq i} K_j$, $i = 1, 2, \ldots, k$ do not intersect, we can write the following formula for the evaluation of the dead zone (zone outside of observation) for all radiolocation stations:

$$V = \sum_{i=1}^{k} V_i. \tag{4}$$

From a mathematical point of view, the problem of the minimum dead zone (zone outside of observation) of radiolocation stations operating together can be formed as follows:

- it is required to find such coordinates (x_i, y_i, z_i) for which the conditions (1) are satisfied and in this case the functional (4) takes a minimum value.

Note that the functional (4) is defined in the non-convex set $K_i \setminus \bigcup_{j\neq i} K_j$ and it is very difficult to give a general solution to such minimization problem. Therefore, the value of this type of functional is calculated by numerical methods. On the other hand, the location of radiolocation stations cannot be arbitrary according to the existing infrastructure. Taking into account what has been said , it is suggested to find a rational solution to the problem. Thus, the best of the possible options proposed for the location of the stations can be considered as rational solution. In order to find a rational solution, a discrete version of the model (1)-(4) is written and functionals (4) are calculated for the proposed location options and compared with each other.

Examples on location option evaluation

1. Suppose that four RLSs of the same type are placed at the vertices of the square geometrically (Fig. 3).

Considering that the minimum distance (side of the square) between the radar stations is $l_0 = 15\ km$, the dead gap angle of each RLS is $\alpha = 130°$ and the detection distance of RLS is $D_{max} = 30\ km$, we can find the volume V_0 of the dead zone of each RLS considered separately and the volume V of the dead zone which is caused by the joint location of these stations.

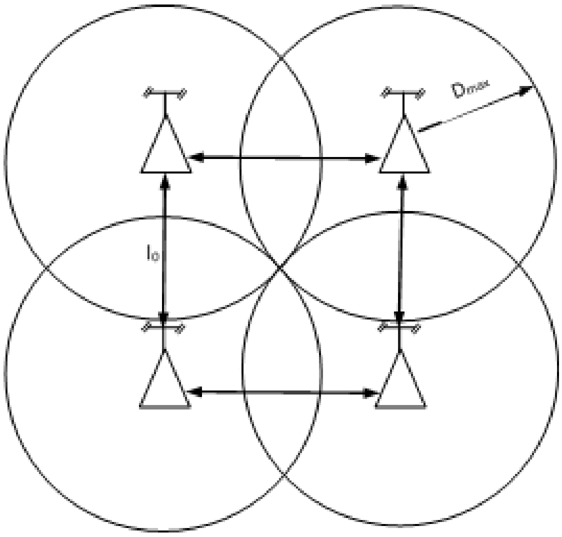

Fig. 3. Schematic representation of the placement of RLSs at the vertices of a square geometrically

According to the data of the problem

$$h = 30\,\mathrm{ctg}\frac{130°}{2} \approx 13\ km$$

and if we apply the formula (2), we obtain

$$V_0 = \pi\left(\frac{30}{14}\right)^2 \int_0^{14} z^2 dz \approx 12252\ [km^3],$$

$$V_i \approx 6945\ [km^3], i = 1, 2, 3, 4.$$

Then

$$V = \sum_{i=1}^{4} V_i \approx 27781\ [km^3].$$

Thus, when comparing, it can be seen that V is about 1.6 times less than $4V_0$.

2. Suppose that 3 radiolocation stations of the same type are placed at the vertices of an equilateral triangle (Fig.4).

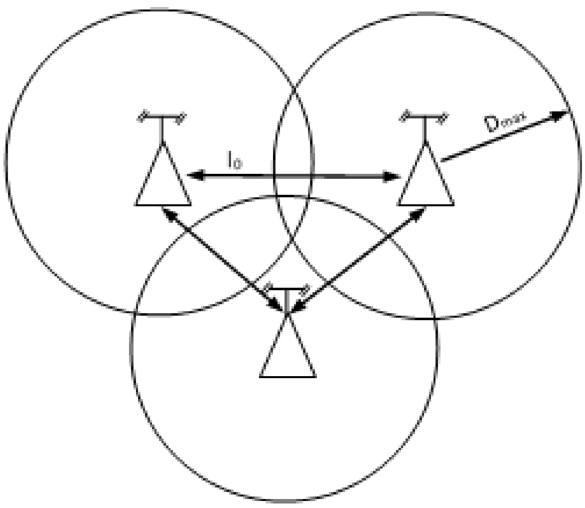

Fig. 4. Schematic representation of the placement of RLSs at the vertices of a triangle geometrically

Taking into account that the minimum distance between radiolocation stations (side of the triangle) is $l_0 = 10\ km$, the angle of the dead zone of each RLS is $\alpha = 120^\circ$, the detection distance of the RLS is $D_{max} = 35\ km$, it is possible to evaluate the separate dead zone of each RLS V_0 and the total sector V.

Based on the data, $h = 35\,\mathrm{ctg}\frac{120°}{2} \approx 20\ km$. Then

$$V_0 = \pi\left(\frac{35}{20}\right)^2 \int_0^{20} z^2 dz \approx 25656\ [km^3],$$

$$V_i \approx 18362\ [km^3], i = 1, 2, 3$$

and

$$V = 3 \cdot V_i \approx 55088\ [km^3].$$

Thus, comparing $3V_0$ and V it can be seen that the total dead zones of RLSs are reduced by about 1.3 times.

Aspects (opportunities) of practical application. The mathematical model for assessing radar dead zones does not impose additional conditions and restrictions related to the geography of the coverage area or the frequency of the operating range of the radio equipment used.

Therefore, if the task of estimating radar dead zones is being solved, the proposed approach can be applied in other areas of radar application.

The discussion of the results

It should also be noted that the proposed approach is based on the assumption that radar stations operate in a rather limited area and are located on a conditional plane. Comparing it with widely used radar systems, as well as with other methods for detecting flying objects (aircraft, helicopters, UAVs, missiles, etc.), we can draw the following conclusions:

- this method does not require the installation of additional equipment and antennas on the radar that implement radiation patterns;
- the mathematical apparatus is simple and easy to implement for assessing the dead zones of jointly operating radars, depending on their layouts.

Conclusions

From the comparison of the obtained numbers, it can be concluded that the creation of a radiolocation area by placing RLSs on the vertices of equilateral triangles (in the form of a checkerboard) is more economically profitable, as it requires fewer stations.

Although advantageous in terms of cost savings, Fig. 4 grouping does not satisfy other critical requirements. For example, the failure of any of the RLSs leads to the formation of large gaps in the radiolocation field. Losses of air targets during tracking will be observed even with the correct operation of all RLSs, since the "dead zones" in the sighting zones of RLSs are not closed.

If we also take into account the distortion of the visual zones of RLSs as a result of the influence of the nature of the relief around the positions, we can generally conclude that the grouping in Fig. 4 can be used only in exceptional cases- with an acute shortage of funds and in secondary areas, but their use at the forefront is not effective.

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Оцінка мертвої зони сумісно працюючих радарів

Гашимов Е. Г., Магаррамов Р. Р., Сабзиев Е. Н., Пашаев А. Б.

Аннотация. Актуальність дослідження. З появою безпілотних літальних апаратів значно актуалізувались і завдання боротьби з ними. Сьогодні оперативне протидія БПЛА має велике значення. Сучасні BPLA здатні не тільки вести відеорозвідку у визначеній місцевості, але й тривалий час спостерігати за конкретним об'єктом і носити по ньому удари. Після виявлення та ідентифікації БПЛА засобами РЛС необхідно прийняти заходи щодо їх знешкодження. У роботі створена математична модель оцінки мертвої зони спільної роботи РЛС для ефективного виявлення безпілотних летальних апаратів і проведено порівняння мертвих зон на конкретних прикладах. Ціль дослідження є рішенням задачі ефективного розміщення спільно працюючих РЛС математическими методами при неспостережуваній залишковій частині їх мінімального об'єму та вибором необхідної схеми розміщення. В статті вирішуються наступні завдання: аналіз характеристик радіолокаційного поля; розробка математической моделі оцінки мертвої зони місцевих радіолокаційних станцій; оцінка деяких варіантів розміщення. Для вирішення завдань використовуються наступні методи дослідження: теоретичний аналіз, математичне моделювання, порівняльний аналіз. Були отримані наступні результати: позначено зменшення мертвої зони в 1,6 раза при чотирьохстанційній схемі квадратного розташування та в 1,3 раза при трьохстанційній треугольній схемі розташування. Виводи: Із порівняння отриманих можна зробити висновок, що створення радіолокаційної зони шляхом розміщення РЛС по вершинам рівносторонніх треугольников (у вигляді шахматної доски) економічно вигідніше, так як вимагає меншої кількості станцій.

Ключові слова: безпілотні літальні апарати, мертва зона, радіолокаційна зона, ефективна зона відображення, станція радіолокації.