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Methods for Calculating the Radio Jamming Zones of Jamming Transmitters Against the Receivers of Unmanned Aerial Vehicle Control Radio Links

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The experience of the Russian-Ukrainian war shows that an effective way to counteract unmanned aerial vehicles is by jamming the receivers of their radio control channels. For this purpose, short-range electronic warfare systems are widely used in the tactical level. During the formulation of requirements for such systems, as well as the planning of their intended use, there is a need to calculate their effective zones of action. A mathematical model for the process of radio jamming unmanned aerial vehicles control channels receivers, which takes into account the technical parameters of the radio channel and the jamming transmitter, the heights of their antennas, and their radiation patterns are developed in the article. It is shown that the radio jamming zone of an interference transmitter with an omnidirectional antenna is limited by a sphere in space, and by circles on the ground surface, the centers of which are shifted relative to the location of the jamming system. The use of directional antennas makes it possible to increase the range of the jamming transmitter, but the jamming zone will be sectoral in space, and its shape will depend on the antenna's radiation pattern. Four methods for calculating the radio jamming zones of jamming transmitters against unmanned aerial vehicles control channel receivers, corresponding to the most common practical cases of their application, are proposed in the article. Software for calculating and graphically displaying the jamming zones has been developed in the MATLAB programming environment. Examples of using the proposed methods for calculating the radio jamming zones of individual protection active jamming systems with "dome-type" antennas and group protection systems with directional antennas are given.

Keywords: method; electronic warfare; radio jamming; interference transmitter; jamming zone; unmanned aerial vehicle

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Introduction

The experience of the Russian–Ukrainian war shows that radio-controlled Unmanned Aerial Vehicles (UAVs) are widely used in the combat zone to perform a wide range of tasks [1–3]: reconnaissance, striking weapons, military equipment, and personnel, remote mining, etc. The enemy's mass employment of UAVs, as well as their continuous improvement, necessitates the advancement of counter-UAV capabilities.

An effective method of countering radio-controlled UAVs is the jamming of receivers in their radio control links [4]. To achieve this short-range Electronic Warfare (EW) systems are widely used at the tactical level, consisting of radio emission detection means (detectors) and Jamming Transmitters (JT).

Planning the employment of EW assets to protect designated objects (including the number of units, their positioning, etc.), as well as defining their technical

requirements, requires the calculation of their effective coverage areas. Therefore, the development of methods for calculating radio jamming zones of JT is a pressing practical and scientific task.

By definition, a jamming zone is a region of space (or its projection onto the Earth's surface) within which EW equipment ensures the suppression of targets with an effectiveness not lower than a specified level [5]. In this work, to distinguish between three-dimensional and two-dimensional jamming zones, the following terms are used: the spatial jamming zone (3D) and the surface jamming zone (2D). The latter is the projection onto the Earth's surface of the spatial jamming zone for a given UAV flight altitude.

Related Works

In [6], the capabilities of EW systems for the jamming of telecommunication systems by various types of

radio interference are considered. Formulas are provided for evaluating the impact of jamming on the receiver of a radio link, based on an analysis of free-space path loss. Among the technical parameters of the JT and the radio link, only their effective radiated power is taken into account.

In [7], a mathematical expression is derived for calculating the maximum jamming range of airborne radar systems. The calculations take into account free-space propagation losses and atmospheric attenuation of radio signals, the transmitter powers of both the jamming system and the radar, the antenna gains and polarization matching, as well as the bandwidth of the radar receiver's linear section and the Amplitude–Frequency Spectrum (AFS) of the radio interference.

In [8], approaches are presented for determining the impact of radio interference on receivers of communication systems and radar stations. The degree of impact is determined by the Signal-to-Interference Ratio (SIR) at the input of the radio receiver. In the calculations, only free-space path loss is taken into account.

In [9], a mathematical expression is derived for calculating the jamming range of a UAV radio control link for a JT with an omnidirectional antenna. The calculations take into account only the transmitter power and the threshold interference power at the receiver input required for its suppression.

In [10], expressions are presented for calculating the jamming zone of a UAV control channel for a jamming transmitter with an omnidirectional antenna that emits frequency-targeted interference. An example for calculating the jamming zone of radio links of commercial UAVs operating in the 2.4 GHz band is provided.

Thus, existing publications consider a number of approaches to determining the jamming range, as well

as constructing jamming zones on the surface, which are carried out with a number of limitations and assumptions. In particular, the antenna height, the shape of their radiation patterns, and the type of interference are not taken into account. Furthermore, the analyzed sources lack methodologies for calculating the jamming zones of UAV radio links.

Problem Statement

The aim of the article is to develop methodologies for calculating the radio jamming zones of JT against the receivers of UAV control radio links.

Statement of Materials

The positioning of the elements of the Unmanned Aircraft System (UAS) control radio channel and the JT is schematically presented in Fig. 1. A topocentric coordinate system [11] is used for positioning the UAS and JT elements. Its origin corresponds to the location of the JT ($x_j = 0, y_j = 0, z_j = 0$), and the x -axis is directed toward the Ground Control Station (GCS), which is located at a distance $x_c = D_{jc}$ from the JT.

In Fig. 1, the following notations are used: J – JT; U – UAV; C – GCS; D_{jc} – orthodromic distance from the JT to GCS; H_j, H_c, H_u – antenna heights of the JT, GCS, and UAV; x_u, y_u, z_u – UAV coordinates in the Cartesian coordinate system; φ_u, θ_u, R_u – UAV coordinates in the spherical coordinate system; φ_u, r_u – coordinates of the projection of the UAV's location onto the Earth's surface (onto the plane xy) in the polar coordinate system; R_j, R_c – slant ranges from the UAV antenna to the JT and GCS antennas, respectively.

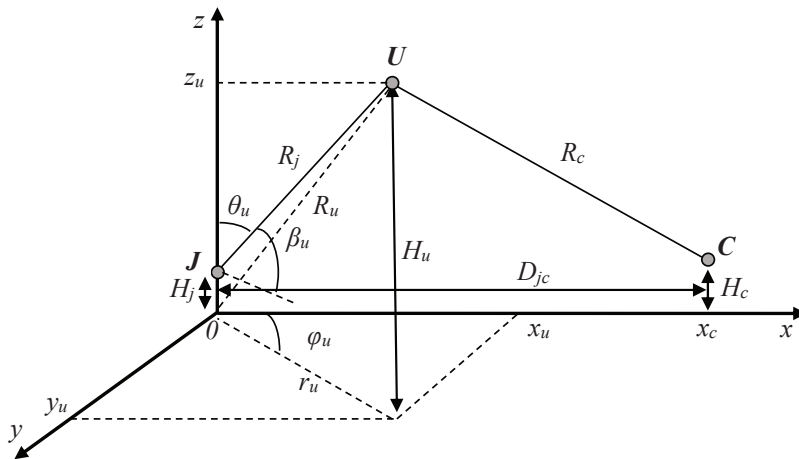


Fig. 1. Graphical representation of the spatial positions of the JT, GCS, and UAV

The power density of the radio signal from the GCS transmitter P_{cj} and of the interference from the JT P_{uj} at the input of the UAV receiver can be calculated using analytical expressions that take into account free-space propagation losses of radio waves [12, 13]:

$$\begin{aligned} P_{uc} &= \sqrt{\frac{P_c G_{cu} G_{uc} \gamma_c \lambda^2}{(4\pi)^2 R_c^2 B_c}}; \\ P_{uj} &= \sqrt{\frac{P_j G_{ju} G_{uj} \gamma_j \lambda^2}{(4\pi)^2 R_j^2 B_j}}, \end{aligned} \quad (1)$$

where

P_j, P_c – transmitter powers of the JT and GCS, respectively;

B_j, B_c – bandwidths of the interference and the radio signal;

G_{ju} – gain of the JT antenna in the direction of the UAV;

G_{uj} – gain of the UAV antenna in the direction of the JT;

G_{cu} – gain of the GCS antenna in the direction of the UAV;

G_{uc} – gain of the UAV antenna in the direction of the GCS;

γ_j, γ_c – coefficients accounting for losses due to polarization mismatch between the antennas of the JT / GCS and the UAV antenna [14];

λ – wavelength corresponding to the operating frequency of the UAS control channel.

For the radio jamming of a UAV receiver, the interference power must exceed the radio signal power by K_p times ($P_j \geq K_p P_c$), where K_p is a coefficient that indicates the minimum required ratio of interference power to signal power at the input of the suppressed receiver, within the bandwidth of its linear section, at which the specified jamming effectiveness (criterion) is ensured [15].

Taking K_p into account, one can derive the equation from (1) that describes the boundary of the jamming zone:

$$R_c^2 = K_a R_j^2; \quad K_a = \frac{P_c G_{cu} G_{uc} \gamma_c B_j K_p}{P_j G_{ju} G_{uj} \gamma_j B_c}, \quad (2)$$

where K_a – a coefficient that accounts for the technical parameters of the JT, the GCS, and the UAV.

We obtain the solutions to equation (2) for the two most common practical cases.

Case 1. JT with an Omnidirectional Antenna

The coefficients $G_{ju}, G_{uj}, G_{cu}, G_{uc}$ are constant and equal to the antenna gains of the JT, the UAV, and the GCS, respectively. This assumption is valid when calculating the jamming zones of JT whose antennas have a “dome-type” radiation pattern (with a beamwidth of 360° in azimuth and 180° in elevation). When

calculating the jamming zone for the upper hemisphere, it can be assumed that $G_{ju} = G_j$, where G_j is the gain of the JT antenna. Omnidirectional antennas are primarily used for the UAV control links; therefore, $G_{uj} = G_{uc} = G_u$, where G_u is the gain of the UAV antenna. In the GCS radio control link, both omnidirectional and directional antennas can be employed. Given the significant distance between the GCS and the protected object (over 3 km), and the constant orientation of the antenna toward the UAV's flight path, it can be assumed that within the jamming zone, the UAV will remain within the main lobe of the GCS radiation pattern. Thus, $G_{cu} \approx G_c$, where G_c is the gain of the GCS antenna. Consequently, for this case, the coefficient K_a (2) will be a constant value and is defined as:

$$K_{a0} = \frac{P_c G_c G_u \gamma_c B_j K_p}{P_j G_j G_u \gamma_j B_c} = \frac{P_c G_c \gamma_c B_j K_p}{P_j G_j \gamma_j B_c}. \quad (3)$$

Case 2. JT with a Directional Antenna

The coefficients G_{uj}, G_{cu}, G_{uc} are constant and equal to the antenna gains of the UAV and the GCS, while the coefficient G_{ju} depends on the azimuth and elevation angle $G_{ju} = G_j F(\varphi_u, \beta_u)$, where $F(\varphi_u, \beta_u)$ is a function describing the normalized radiation pattern of the JT antenna. This case corresponds to the use of directional antennas in the jammer to form a sectoral jamming zone (the operating sector of the jamming station) [5]. In this instance, the coefficient K_a depends on the angles φ_u and β_u :

$$K_{as}(\varphi_u, \beta_u) = \frac{P_c G_c \gamma_c B_j K_p}{P_j G_j B_c \gamma_j F(\varphi_u, \beta_u)} = \frac{K_{a0}}{F(\varphi_u, \beta_u)}. \quad (4)$$

For simplified calculations of the sectoral jamming zone, the antenna directivity of the jammer can be considered only in azimuth; in this case, the coefficient K_a is equal to:

$$K_{ac}(\varphi_u) = \frac{K_{a0}}{F(\varphi_u)}. \quad (5)$$

When calculating the coefficient, both the radiation patterns of real antennas and their approximations can be used. Values close to real ones can be obtained through antenna simulation in specialized software environments such as CST Studio Suite and Altair Feko, or through practical measurements [16, 17]. Approximation of the radiation pattern can be performed using various methods, one of which is the Gaussian function [18]:

$$F(\varphi) = \exp\left(-\left(\frac{2,772}{\varphi_{0,5}^2}(\varphi - \varphi_m)\right)^2\right); \quad (6)$$

$$F(\varphi, \beta) = \exp\left(-\left(\frac{2,772}{\varphi_{0,5}^2}(\varphi - \varphi_m) + \frac{2,772}{\beta_{0,5}^2}(\beta - \beta_m)\right)^2\right), \quad (7)$$

where φ_m, β_m – the direction of the main lobe maximum of the radiation pattern;

$\varphi_{0,5}$, $\beta_{0,5}$ – the half-power beamwidth of the radiation pattern.

Approximation of the radiation pattern using a Gaussian function is computationally simple, easily scalable to any beamwidth, and produces a smooth pattern without sidelobes. In most practical cases, such an approximation is sufficient for constructing jamming zones.

For a given antenna beamwidth, the antenna gain can be approximately calculated as [19]:

$$K_j \approx \frac{4\pi}{\Omega_A} = \frac{4\pi}{\left(\frac{\pi}{180}\right)^2 \varphi_{0,5}^o \beta_{0,5}^o} = \frac{41253}{\varphi_{0,5}^o \beta_{0,5}^o}, \quad (8)$$

where $\varphi_{0,5}^o$, $\beta_{0,5}^o$ – the half-power beamwidth in degrees; Ω_A – the beam solid angle.

For planar antennas, a better approximation to (8) is [19]:

$$K_j \approx \frac{32400}{\varphi_{0,5}^o \beta_{0,5}^o}. \quad (9)$$

Solution of the Jamming Zone Equation for a JT with an Omnidirectional Antenna

Let us use the well-known formulas for calculating the distance between two points in a Cartesian coordinate system [20] and express the slant ranges from the UAV to the JT and the GCS as $R_j^2 = x_u^2 + y_u^2 + (H_j - z_u)^2$ and $R_c^2 = (D_{jc} - x_u)^2 + y_u^2 + (H_c - z_u)^2$. Substituting these values into equation (2) and grouping by the variables x_u , y_u , z_u we obtain:

$$x_u^2 - \frac{2D_{jc}}{1 - K_{a0}}x_u + y_u^2 + z_u^2 + \frac{2(K_{a0}H_j - H_c)}{1 - K_{a0}}z_u + \frac{D_{jc}^2 + H_c^2 - K_{a0}H_j^2}{1 - K_{a0}} = 0. \quad (10)$$

Equation (10) defines the boundary of the spatial jamming zone within a Cartesian coordinate system and can be written as an expression describing a spherical surface:

$$(x_u - x_0)^2 + y_u^2 + (z_u - z_0)^2 = R_s^2; \quad (11)$$

$$x_0 = \frac{D_{jc}}{1 - K_{a0}}; \quad z_0 = \frac{H_c - K_{a0}H_j}{1 - K_{a0}}; \quad (12)$$

$$R_s = \sqrt{x_0^2 + z_0^2 - \frac{D_{jc}^2 + H_c^2 - K_{a0}H_j^2}{1 - K_{a0}}}.$$

Analysis of expressions (11)–(12) leads to the conclusion that the boundary of the spatial jamming zone is a sphere with a radius R_s whose center is shifted by x_0 and z_0 .

In practice, when calculating object protection zones [5], it is more convenient to use the surface jamming zones obtained for different UAV flight altitudes, which represent projections of the spatial jamming zone onto the ground surface (xy plane in Fig. 1). The surface jamming zones can be determined using

the results of calculations (11)–(12), however, it is advisable to derive expressions with lower computational complexity. To achieve this, we replace the variable z_u in equation (10) with H_u , which corresponds to the UAV flight altitude, and obtain it in the following form:

$$(x_u - x_0)^2 + y_u^2 = r_s^2; \quad (13)$$

$$r_s = \sqrt{x_0^2 - \frac{D_{jc}^2 + (H_c - H_u)^2 - K_{a0}(H_j - H_u)^2}{1 - K_{a0}}}. \quad (14)$$

As follows from expressions (13)–(14), the boundary of the surface jamming zone for altitude H_u is a circle with radius r_s , whose center is shifted along the axis x by x_0 .

In many practical cases of jamming zones calculations, the antenna heights of the GCS and the JT can be neglected by assuming them equal to zero ($H_j = H_c = 0$). Then expressions (12) and (14) can be simplified to:

$$x_0 = \frac{D_{jc}}{1 - K_{a0}}; \quad z_0 = 0; \quad (15)$$

$$R_s = |x_0| \sqrt{K_{a0}}; \quad r_s = \sqrt{K_{a0}x_0^2 - H_u^2}.$$

Analysis of expressions (11)–(15) leads to the following conclusions.

1. The boundary of the spatial jamming zone is formed by a sphere with radius R_s , and the surface jamming zone by a circle with radius r_s (Fig. 2–Fig. 3).

2. The center of the sphere is shifted relative to the JT location by x_0 and z_0 .

The value x_0 depends on the distance between the JT and the GCS, as well as their technical parameters accounted for by coefficient K_{a0} . The shift z_0 depends on the antenna heights of the jammer and the control station, as well as coefficient K_{a0} .

3. If the coefficient $K_{a0} > 1$, the jamming zone in space is located inside the sphere, and on the surface, it is within the circle. As the value K_{a0} decreases, which corresponds to improved JT performance (increased power, use of more effective interferences, etc.), the offset along the x axis increases in the direction opposite to the GCS, and the radii R_s and r_s of the jamming zones increase. For $K_{a0} = 1$, the boundary of the jamming zone passes midway between the JT and the GCS.

4. If the coefficient $K_{a0} < 1$, the jamming zone in space is located outside the sphere, and on the surface, it is outside the circle. In this case, as K_{a0} decreases, the offset along the x axis increases from the GCS position x_c in the direction opposite to the JT.

5. As the UAV flight altitude increases, the size of the circle describing the boundary of the surface jamming zones decreases. The minimum orthodromic jamming range of the JT D_j^{\min} is always in the direction toward the GCS and is calculated as:

$$D_j^{\min} = |r_s - |x_0||. \quad (16)$$

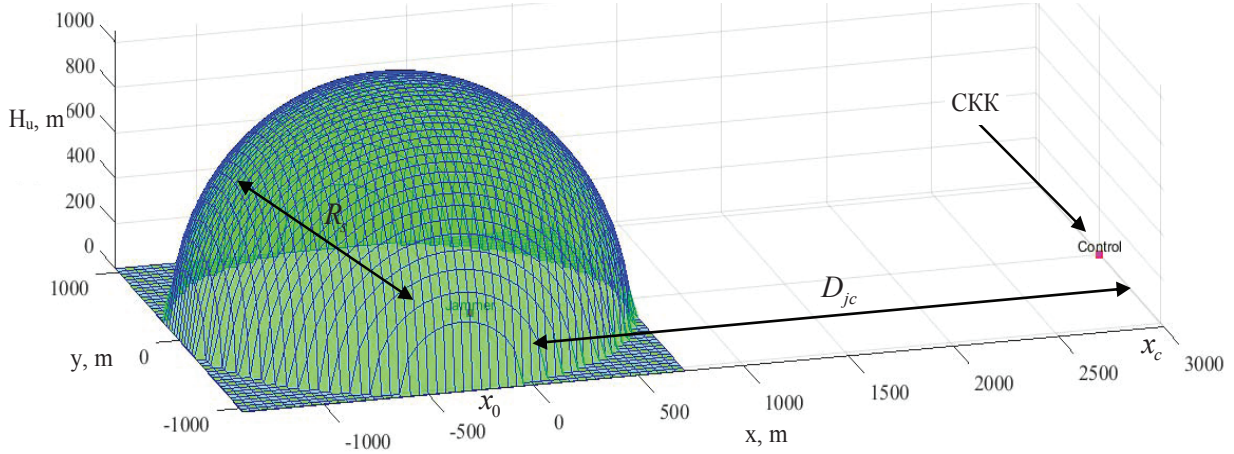


Fig. 2. The spatial jamming zone for $K_{a0} = 10$; $H_j = 0$; $H_c = 0$

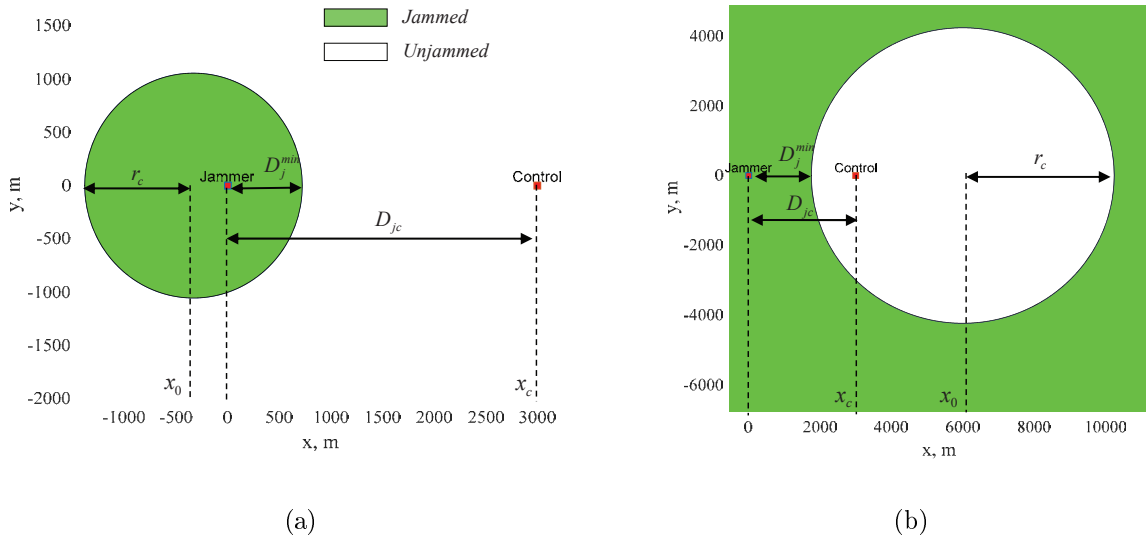


Fig. 3. The surface jamming zones for $H_u = 20$; $H_j = 0$; $H_c = 0$ and: (a) $K_{a0} = 10$; (b) $K_{a0} = 0, 5$

Solution of the Jamming Zone Equation for a JT with a Directional Antenna

To calculate the boundary of the jamming zone for a JT with a directional antenna in 3D space, it is necessary to express equation (11) in a spherical coordinate system.

The coordinates in the Cartesian system are related to the spherical coordinates by the following expressions:

$$\begin{aligned} x_u &= R_u \cos \beta_u \cos \varphi_u; \\ y_u &= R_u \cos \beta_u \sin \varphi_u; \quad z_u = R_u \sin \beta_u, \end{aligned} \quad (17)$$

where R_u, φ_u, β_u – the UAV position in the spherical coordinate system.

Substituting (17) into (11), we obtain the equation of a sphere describing the boundary of the spatial

jamming zone in spherical coordinates:

$$R_u^2 - 2(x_0 \cos \beta_u \cos \varphi_u + z_0 \sin \beta_u) R_u + x_0^2 + z_0^2 - R_s^2 = 0. \quad (18)$$

Expression (18) is a monic quadratic equation with the coefficients [21]:

$$\begin{aligned} p &= 2(x_0 \cos \beta_u \cos \varphi_u + z_0 \sin \beta_u); \\ q &= x_0^2 + z_0^2 - R_s^2. \end{aligned} \quad (19)$$

To compute R_u for given angles φ_u, β_u , the solution of equation (18) is found using known formulas [22]:

$$D = p^2 - 4q; \quad R_{u1,2} = \frac{-p \pm \sqrt{D}}{2}, \quad (20)$$

where D – the discriminant of a monic quadratic equation.

The values $R_{u1,2}$ obtained from (20) are taken as positive, since the radius cannot be negative.

The boundary of the jamming zone in space is a three-dimensional figure formed by points on spherical surfaces (18), calculated for angles within ranges $\varphi_u = [-\pi \pi]$, $\beta = [0 \pi/2]$, taking into account the normalized antenna radiation pattern of the JT in a given direction according to expression (4).

Thus, the calculation of the spatial jamming zone is performed using expressions (12), (19), and (20) for various angles φ_u and β_u . For this purpose, the coefficient $K_{as}(\varphi_u, \beta_u)$ is used in (12) instead of the constant K_{a0} .

Let us derive an expression for calculating the surface jamming zone considering only the azimuth radiation pattern of the JT antenna. For this, we rewrite the equation of the circle (13) in a polar coordinate system, taking into account [20]:

$$x_u = r_u \cos \varphi_u; \quad y_u = r_u \sin \varphi_u, \quad (21)$$

where r_u , φ_u – the polar coordinates of the UAV ground projection.

Substituting (21) into (13), we obtain:

$$r_u^2 - 2x_0 \cos \varphi_u r_u + x_0^2 - r_s^2 = 0. \quad (22)$$

Expression (22) is a monic quadratic equation with coefficients (23), the solution of which is obtained using formulas (20).

$$p = 2x_0 \cos \varphi_u; \quad q = x_0^2 - r_s^2. \quad (23)$$

When calculating parameters x_0 and r_s using expressions (10) and (14) for different azimuth values $\varphi_u = [-\pi \pi]$, it should be taken into account that coefficient K_a depends on φ_u according to (5).

Based on the developed mathematical framework, four methods for calculating jamming zones was developed.

Method for Calculating the Spatial Jamming Zone of a JT with an Omnidirectional Antenna

The input data for the calculation include the GCS parameters ($P_c, G_c, B_c, \gamma_c, H_c$) and the JT parameters ($P_j, G_j, B_j, \gamma_j, H_j, K_p$).

The method consists of 4 steps.

1. Calculation of the coefficient K_{a0} using (3).
2. Calculation of the sphere center coordinates x_0, z_0 , and its radius R_s using (12).
3. Calculation of the coordinate arrays for the points forming the sphere in a Cartesian coordinate system:

$$\begin{aligned} y_u [i, j] &= \pm \sqrt{R_s^2 - (x_u [i] - x_0)^2 - (z_u [j] - z_0)^2}; \\ x_u [i] &\in [x_0 - R_s \quad x_0 + R_s]; \\ z_u [j] &\in [z_0 - R_s \quad z_0 + R_s]. \end{aligned} \quad (24)$$

4. The jamming zone is located inside the sphere if $K_{a0} > 1$; otherwise, it is outside its boundaries.

Method for Calculating the Surface Jamming Zone of a JT with an Omnidirectional Antenna

The input data for the calculation include the GCS parameters ($P_c, G_c, B_c, \gamma_c, H_c$), the JT parameters ($P_j, G_j, B_j, \gamma_j, H_j, K_p$) and the UAV altitude H_u .

The method consists of 5 steps.

1. Calculation of the coefficient K_{a0} using (3).
2. Calculation of the circle center shift x_0 and its radius r_s using (12) and (14).
3. Calculation of the minimum jamming range D_j^{\min} using (16).
4. Calculation of coordinate arrays forming the circle in Cartesian coordinates:

$$\begin{aligned} y_u [i] &= \sqrt{r_s^2 - (x_u [i] - x_0)^2}; \\ x_u [i] &\in [x_0 - r_s \quad x_0 + r_s]. \end{aligned} \quad (25)$$

5. The jamming zone lies inside the circle if $K_{a0} > 1$, otherwise outside it.

Method for Calculating the Spatial Jamming Zone of a JT with a Directional Antenna

The flowchart representing the stages of the method is shown in Fig. 4a.

The input data for the calculation include the GCS parameters ($P_c, G_c, B_c, \gamma_c, H_c$) and the JT parameters ($P_j, G_j, B_j, \gamma_j, H_j, K_p$), as well as the function describing the JT antenna's normalized radiation pattern in 3D space $F(\varphi_u, \beta_u)$ (block 1).

The method consists of the following steps.

1. Calculation of the coefficient K_{a0} using (3) (block 2).
2. Formation of two loops for varying azimuth and elevation angles with steps $\Delta\varphi$ and $\Delta\beta$, calculation of the sphere center coordinates x_0, z_0 , and radius R_s using (12) (blocks 3–5).
3. Calculation of slant jamming ranges R_{u1} and R_{u2} using (19) and (20); if the value is positive, it is added to the array $R_u(\varphi_u, \beta_u)$ (block 6).
4. Calculation of the jamming zone boundary in Cartesian coordinates $x_u(\varphi_u, \beta_u)$, $y_u(\varphi_u, \beta_u)$, using (17) (block 7).
5. The jamming zone lies within the three-dimensional figure defined by $x_u(\varphi_u, \beta_u)$, $y_u(\varphi_u, \beta_u)$, $z_u(\varphi_u, \beta_u)$.

Method for Calculating the Surface Jamming Zone of a JT with a Directional Antenna

The flowchart representing the stages of the method is shown in Fig. 4b.

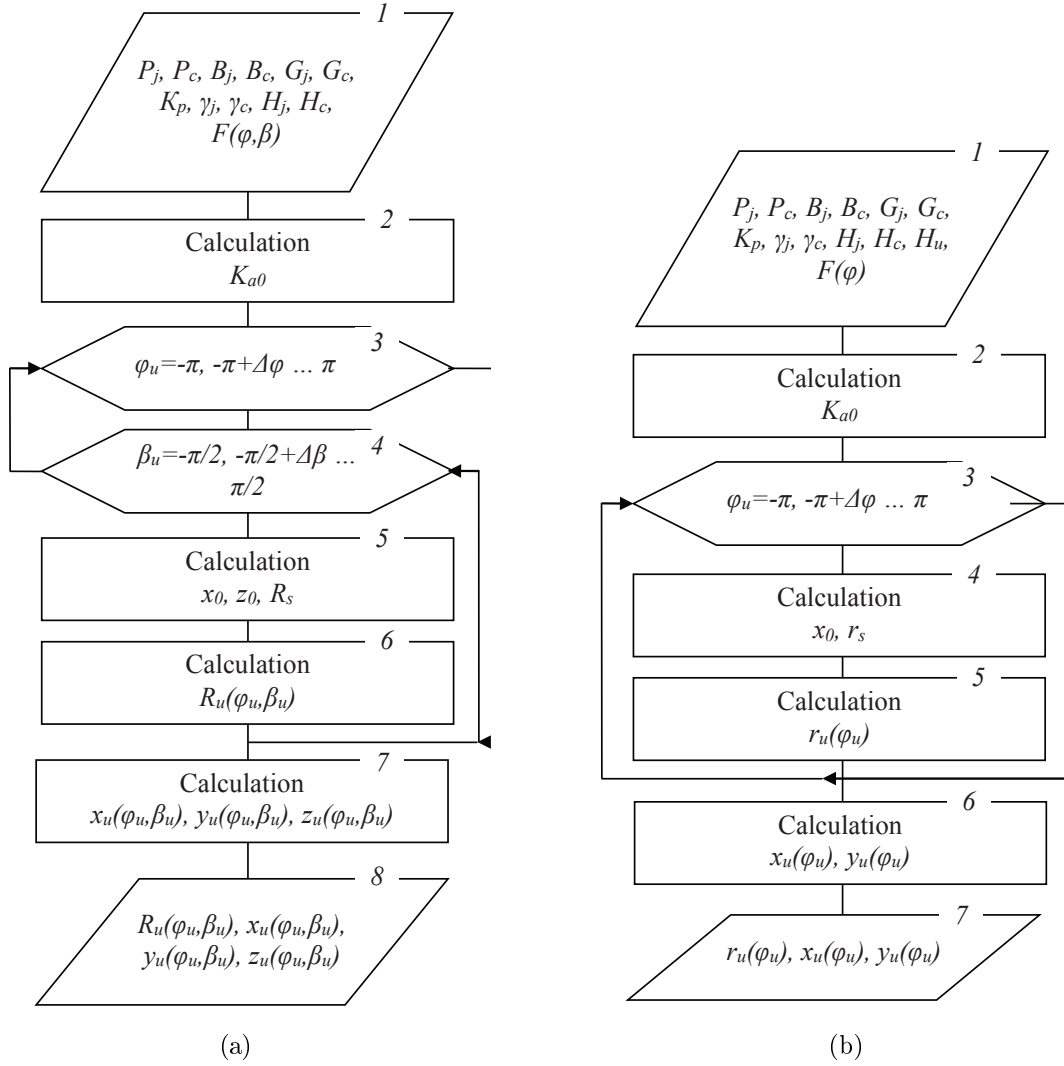


Fig. 4. The flowchart of the method for calculating the jamming zones: (a) in space; (b) on the surface

The input data for the calculation include the GCS parameters ($P_c, G_c, B_c, \gamma_c, H_c$) and the JT parameters ($P_j, G_j, B_j, \gamma_j, H_j, K_p$), the function describing the JT antenna's normalized radiation pattern in the azimuthal plane $F(\varphi_u)$ and the UAV altitude H_u (block 1).

The method consists of the following steps.

1. Calculation of the coefficient K_{a0} using (3) (block 2).

2. Formation of a loop to vary the azimuth values with a specified step $\Delta\varphi$ (block 3).

3. Calculation of the circle center shift x_0 , which defines the boundary of the jamming zone, and its radius r_s using formulas (10) and (14) (block 4).

4. Calculation of the orthodromic jamming ranges r_{u1} and r_{u2} using expressions (20) and (23); if the value is positive, it is added to the array $r_u(\varphi_u)$ (block 5).

5. Calculation of the boundary of the jamming zone in the Cartesian coordinate system $x_u(\varphi_u), y_u(\varphi_u)$, according to expressions (21) (block 6).

6. The surface jamming zone is located within the two-dimensional figure described by the coordinates $x_u(\varphi_u), y_u(\varphi_u)$.

Based on the proposed methods, software was developed in the MATLAB environment to determine and visualize jamming zones.

Let us consider two examples of applying the proposed methods and software for calculating jamming zones of short-range EW systems.

Calculations were performed for the jamming of a UAV control link with a First Person View system, which has the following technical parameters: $P_c = 3$ W; $G_c = 10$ dBi; $B_c = 500$ kHz; $\gamma_c = 0$ dB. The radio link operates on the ExpressLRS protocol in 50 Hz mode. This mode utilizes a LoRa (Long Range) standard radio signal with a Spreading Factor $SF = 8$.

Assume that the EW system emits a periodic frequency-sweeping interference. In this case, the jamming coefficient calculated for a radio channel with parameters $SF = 8$ and $B_c = 500$ kHz is $K_p = 13$ dB [23].

The distance between the JT and the GCS is taken as $D_{jc} = 5000$ m, with the following antenna heights: $H_j = 2$ m; $H_c = 4$ m.

Calculation of jamming zones for a JT with an omnidirectional antenna

The input data correspond to a typical short-range EW system used for individual object protection [24]. Such jammers typically employ “dome-type” radiation pattern antennas (beamwidth 360° in azimuth and 180° in elevation) with the following technical parameters: $P_j = 50$ W; $G_j \approx 2$ dBi; $B_j = 100$ MHz; $\gamma_j = -3$ dB [25].

A graphical representation of the spatial jamming zone calculated using the developed MATLAB software is shown in Fig. 5a, and its projections for different UAV altitudes (surface jamming zones) are shown in Fig. 5b.

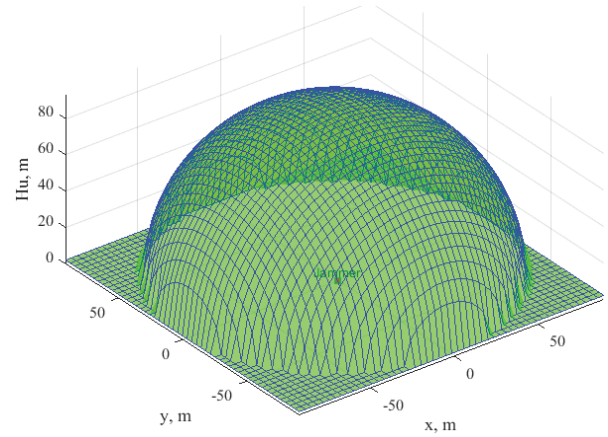
As can be seen from Fig. 5, the spatial jamming zone of a JT with a “dome-type” antenna is bounded by a hemisphere whose center is shifted along the axes x and z by approximately 2 m. The projections of the jamming zone onto the ground surface are circles whose centers are shifted along axis x by 1.7 m. The radius of the circle describing the surface jamming zone decreases with increasing UAV altitude. For example, at an altitude of 20 m it is 87.5 m, while at 90 m it is about 21.9 m. This feature must be taken into account when planning the deployment of short-range EW systems for object protection.

Calculation of jamming zones for a JT with a directional antenna

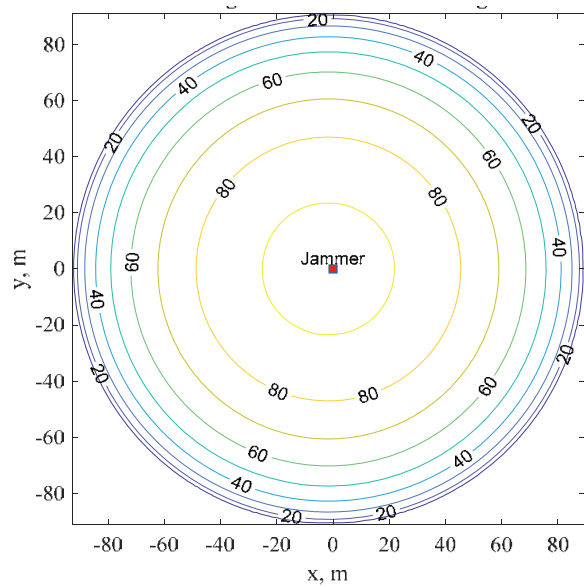
The input data correspond to a typical short-range EW system used for group protection (electronic shielding of a group of objects) [5]. Such jammers use directional antennas to increase jamming range. Let us assume the antenna’s beamwidth values are $\varphi_{0,5}^o = 40^\circ$, $\beta_{0,5}^o = 60^\circ$, with the main lobe directed at $\varphi_m^o = \beta_m^o = 0^\circ$. The antenna gain in this case is $G_j \approx 11,3$ dBi (9). Technical parameters of the JT: $P_j = 100$ W; $B_j = 25$ MHz; $\gamma_j = 0$ dB. The jamming zone will be calculated with angular steps $\Delta\varphi = \Delta\beta = 1^\circ$.

The spatial jamming zone obtained using the developed software is shown in Fig. 6, and its projections depending on UAV altitude (surface jamming zones) are shown in Fig. 7.

From Fig. 6–Fig. 7, it can be seen that the JT is located outside the jamming zone, and its shape depends on the antenna radiation pattern. As UAV altitude increases, the size of the surface jamming zone decreases. For example, the length of the zone along x -axis is 868 m at an altitude of 50 m and 409 m at 300 m.



(a)



(b)

Fig. 5. Jamming zones of a JT with a “dome-type” antenna: (a) in space; (b) on the surface for different UAV altitudes

The obtained calculation results for the jamming zones (Fig. 1–Fig. 5) are consistent with known data regarding the operating range of active jamming systems for individual and group protection [25], which confirms the validity of the proposed methods.

Conclusions

The proposed methods for calculating radio jamming zones take into account the main technical parameters of the transmitting and receiving devices of the UAS control radio link and the JT, the antenna radiation pattern of the JT, as well as the antenna heights of the JT and the GCS.

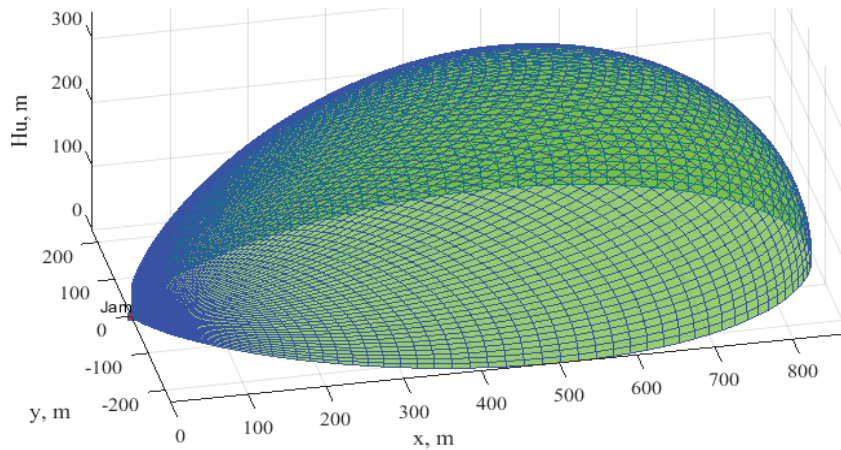


Fig. 6. The spatial jamming zone of a JT with a directional antenna

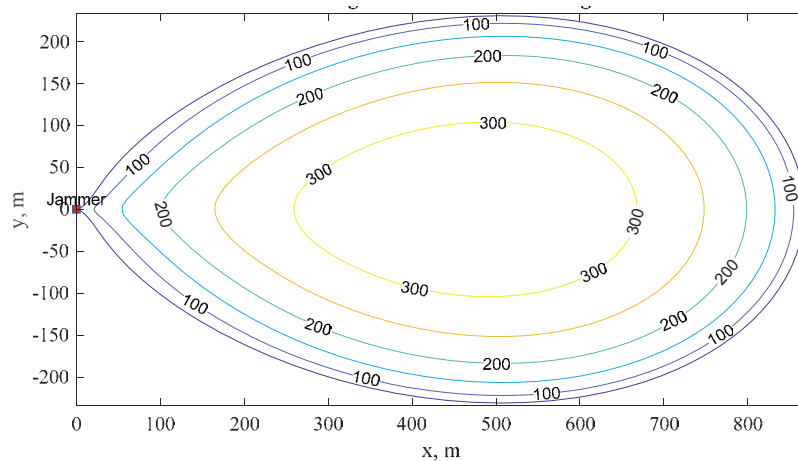


Fig. 7. The surface jamming zones of a JT with a directional antenna for different UAV altitudes

The jamming zone of a JT with omnidirectional antennas is bounded in space by a sphere, and on the surface by circles whose centers are shifted relative to the JT location. When using “dome-type” antennas, the spatial jamming zone takes the form of a hemisphere shifted along the axes x and z relative to the JT. When a directional antenna is used, the shape of the jamming zone depends on the antenna radiation pattern.

The results of calculating jamming zones for short-range EW systems using the proposed methods align with established data on the performance characteristics of JT, which confirms their validity.

Further research in this area should focus on developing methods for calculating jamming zones for telemetry and payload data transmission radio links of UAVs. Furthermore, it is advisable to develop recommendations for the optimal placement of EW systems and UAV flight path planning using the proposed mathematical framework.

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Методики розрахунку зон радіоподавлення передавачів перешкод приймачам каналів управління безпілотних літальних апаратів

Нагорнюк О. А.

Досвід російсько-української війни показує, що ефективним способом протидії безпілотним літальним апаратам є постановка перешкод приймачам їхніх радіоканалів управління. Для цього в тактичній ланці широко застосовуються засоби радіоелектронної боротьби ближньої дії. Під час формування вимог до таких засобів, а також планування застосування їх за призначенням виникає потреба у розрахунку зон їхньої дії. У статті розроблено математичну модель процесу радіоподавлення приймачів каналів управління безпілотних літальних апаратів перешкодами, яка враховує технічні параметри радіоканалу та передавача перешкод, висоти розміщення їхніх антен та діаграми спрямованості. Показано, що зона радіоподавлення передавача перешкод із неспрямованою антеною у просторі обмежується сферою, а на земній поверхні колами, центри яких зміщені відносно місцезоположення засобу радіоподавлення. Використання спрямованих антен дозволяє підвищити дальність дії передавача перешкод, але зона радіоподавлення буде секторною у просторі, а її форма матиме залежність від діаграми спрямованості антени. У статті запропоновано чотири методики розрахунку зон радіоподавлення передавачів перешкод приймачам каналів управління безпілотних літальних апаратів, що відповідають найбільш розповсюдженим практичним випадкам їхнього застосування. Розроблено програмне забезпечення обчислення та графічного відображення зон радіоподавлення у програмному середовищі MATLAB. Наводяться приклади використання запропонованих методик для розрахунку зон радіоподавлення засобів активних перешкод індивідуального захисту із антенами „купольного” типу та групового захисту із спрямованими антенами.

Ключові слова: методика; радіоелектронна боротьба; радіоподавлення; передавач перешкод; зона подавлення; безпілотний літальний апарат