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Evaluation of the effectiveness of the protection of strategically important objects from unmanned aerial vehicles by air defense forces

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Abstract. The relevance of this article is due to the need to protect strategically important objects from terrorist attacks from the air. In particular, the experience of the leading countries of the world shows that the most effective protection of strategically important objects from terrorist acts from the air is a combination of the principles of action of special purpose means, for which it is appropriate to consider some issues of compatibility of these means when protecting strategically important objects from terrorist acts or air attack. At the same time, the study of these issues will make it possible to evaluate the results of joint actions, as well as to develop scientifically based recommendations for their effective application. In this regard, this article is aimed at identifying the factors that, in the modern conditions of the russian-Ukrainian war, have the greatest impact on the effectiveness of engineering protection of strategically important objects. At the same time, taking into account these factors, an evaluation of the effectiveness of the protection of strategically important objects from unmanned aerial vehicles by air defense forces was carried out, the use of which will allow obtaining more correct results. And based on them, develop practical recommendations for increasing the protection of strategically important objects from unmanned aerial vehicles, in particular during hostilities. The article presents a structural and logical scheme of a methodical approach to the selection of the location of air defense means during the protection of strategically important objects from unmanned aerial vehicles, a description of the evaluation stages, the main output data, partial and generalized performance indicators, evaluation criteria and conditions are given. The need to unite the air defense system into a single whole is justified, and the criteria for evaluating the effectiveness of the organization of joint air defense actions are defined. This paper examines the issue of the joint use of air defense and radio-electronic influence during the protection of strategically important objects, the methods of determining the locations of physical influence means, which allows to evaluate the expected results of joint actions, as well as to develop scientifically based recommendations for their effective joint application in the composition of special groups and develop proposals for their special actions in various conditions during the protection and preservation of strategically important objects. The materials of the article are of practical value for management bodies, which, when planning the use of means of physical influence, perform calculations to determine the required volume of engineering measures to increase their survivability during the protection of strategically important objects from unmanned aerial vehicles.

Keywords: strategically important object, unmanned aerial vehicle, air defense forces, electronic warfare.

Introduction

A significant number of strategically important objects, in particular military ones, are located on the territory of most states, the degree of danger of which is established based on the share of the civilian population that falls into the zone of possible neutralization in the event of an accident on it. Strategically important facilities are energy, chemical, food, transport, financial and banking, information technology and telecommunication facilities, utilities: water, heat, gas supply; health care and nuclear industry, arsenals and military warehouses. At the same time, the consequences of accidents at strategically important objects are quite significant. This can result in the destruction or

destruction of infrastructure, cause significant economic losses, and most importantly can lead to the loss of human life.

The role and place of unmanned aerial vehicles in the conduct of military conflicts has led to their massive, integral and global application for the simultaneous solution of many problems. In particular, the development of unmanned aircraft has opened up new opportunities for carrying out terrorist actions from the air against strategically important objects. In particular, the assessment of armed conflicts (Libya, Syria, Nagorno-Karabakh, Ukraine) shows the growing role of unmanned aviation.

One of its important directions is related to the development of unmanned aerial vehicles, the use of which allows minimizing the loss of personnel, due to the replacement of human resources with high-tech means. This allows us to conclude that the enemy is highly likely to start hostilities directly with the use of missile weapons and aviation (including unmanned aircraft) by conducting an air offensive operation. Moving the armed struggle into the air space increases the role of the aviation and anti-aircraft components of the armed forces, the degree of achievement of the strategic goal of military operations will depend on the effectiveness of their application.

If aviation and air defense forces perform the tasks in an air defense operation, then the forces and assets of the ground forces will be able to implement the tasks during the ground part of the armed conflict, otherwise (without aviation and air defense assets) the enemy will achieve strategic goals and the conflict will be exhausted, or no one will perform tasks during the implementation of the ground part of the armed conflict.

The analysis of the russian-Ukrainian war indicates the growing use of unmanned aerial vehicles by the enemy to attack strategically important objects with the aim of destabilizing the situation in the country and reducing its defense capability (Zaluzhny, Moysyuk, Shaptala, 2022; Synyshyn M. M., Demchyshyn V. S., Karasyov D. L., Grinchenko V. V., Babiy Yu. O., Miroshnichenko O. V., 2023). In particular, taking into account these factors, the article evaluates the effectiveness of the protection of strategically important objects from unmanned aerial vehicles by air defense forces, the use of which will allow to obtain more correct results, and based on them to develop practical recommendations for improving them. Fulfillment of this task requires consideration of the conceptual apparatus of the interaction of air defense means and radio-electronic warfare when solving air defense tasks; determination of their compatibility and criteria for evaluating the effectiveness of the organization of interaction during the conduct of air defense by troops (forces).

Materials and Methods

The analysis of modern armed conflicts shows that the most effective protection of objects from terrorist actions from the air is a combination of efforts of special purpose means, for which it is appropriate to consider some issues of compatibility of these means when protecting strategically important objects from terrorist actions or air attack. The study of these issues will allow to evaluate the expected results of joint actions, as well as to develop scientifically based recommendations for their effective application.

This article deals with issues of interaction (Volkov A. F., Yanenko O. A., Kravchenko O. A., 2019) of the joint use of anti-aircraft defense and radio-electronic warfare during the protection of strategically important objects, methods of determining the locations of air defense equipment of defense and electronic warfare (Lezik O. V., Orekhov S. V., Kosenko G. P., 2015), which allows to evaluate the expected results of joint actions, as well as to develop scientifically based recommendations for their effective application as part of special groups and to develop practical recommendations regarding their special actions in various conditions during the protection and preservation of strategically important objects.

Drobakha G. A. (2014) considered the conceptual apparatus of the interaction of air defense means and electronic warfare when solving air defense tasks in the composition of interspecies groups of troops (forces), as well as its essence and content, forms and methods of its organization and implementation.

Volkov A. F. (2019) substantiated the need to unite the air defense system of interaction into a single whole, in particular, he considered the main issues of the usefulness of the relationships of cooperating elements of the interaction system during the air defense of troops (forces) and the dependence of interaction processes on the main properties of the system management, such as sustainability and responsiveness.

Lezik V. O. (2015) established that when assessing the effectiveness of interaction, it is necessary to measure the degree of benefit and usefulness of the relationships of cooperating elements of the interaction system, that is, the effectiveness of the influence of one of the interacting elements of the interaction system on another is measured by the change in the efficiency of the latter. At the same time, the indicators used to characterize each type of impact should reflect not only the positive result (the result of organized interaction), but also the possible negative consequences of unorganized interaction.

During the organization of air defense, the implementation of interoperability, which is a purposeful activity of commanders and largely allows to achieve the specified efficiency of the created air defense system, becomes of great importance. However, at this time there is no unambiguous interpretation of the concept of “compatibility”, which is due to the complexity of its structure and the need to cover the entire content when solving various tasks. The most widespread is the definition of the interaction of troops as agreed on goals, tasks, place, time and methods of performing the tasks of the actions of troops (forces) to achieve the goal of the battle (operation) (Lytvyn M., Allerov Yu., Kyrychenko I., 2003).

In particular, the interaction of troops is considered as one of the most important principles and conditions for the preparation and conduct of operations, the success of which can be achieved only by the united, clearly coordinated efforts of all forces and means based on a single plan and plan of combat operations. However, a significant drawback of the existing definitions of the concept of “compatibility” is that they do not take into account the mutual influence of the actions of troops (forces), which under certain conditions can become important for achieving the overall goal of the operation (battle, hostilities). It is known that the mutual influence of subjects on each other can be both positive and negative. In this regard, for two subjects it is possible to define two opposite types of mutual influence-opposition and interaction.

The main goal of the interaction of troops (forces) is rational use of the combat capabilities of the interacting troops (forces) and ensuring the safety of the troops (forces) involved in solving tasks. The content of the types of interaction is directly determined by the characteristics of the subjects of interaction. In particular, the tactical fire units of air defense may include firearms that are in service with armed formations and other law enforcement agencies, anti-drone nets, anti-cumulative grids and other commercial means. The tactical and special units of radio electronic warfare may include means of radio electronic warfare, means of radio electronic suppression, anti-drone guns and other means based on physical principles of operation. However, despite a sufficiently large number of scientific works, the issue of their interaction in solving the tasks of air defense forces, especially in its applied part, is not sufficiently disclosed. Let's consider the general issues of using anti-aircraft defenses on aircraft that can carry out terrorist actions from the air, in particular unmanned aerial vehicles.

The tasks of the air defense forces are carried out by means of air defense, which is carried out according to a certain plan, agreed on the purpose, task, place and time and aimed at neutralizing unmanned aerial vehicles and counteracting their influence on the objects of defense, or forcing it to refuse to perform specified tasks. Important components of the object's air defense forces are direct

physical impact on aircraft and maneuver (change of location) of air defense forces and electronic warfare means.

Air defense of the object begins from the moment of detection or receipt of information about the appearance of unmanned aerial vehicles and ends with its neutralization or cessation of influence on it.

The main characteristics of the object's anti-aircraft defense are the duration and number of unmanned aerial vehicles that were neutralized. Air defense means, depending on the situation and the tasks performed by them, can be placed directly on the terrain, vehicles, buildings, etc.

The places of their placement should correspond to the task, the level of the protected object, the expected impact of unmanned aerial vehicles and ensure:

a) focusing the main efforts on the preservation of strategically important objects;

b) the most complete use of opportunities for neutralization of unmanned aerial vehicles;

c) continuity and ease of management;

d) continuous interaction with other means involved in the protection of strategically important objects;

e) their rapid movement.

As a rule, no less than 3 places are assigned for the performance of tasks by means of air defense (Lezik O., Piskunov S., Volkov A., Sedyukh V., 2017).

Common places of placement must meet the requirements, in particular:

a) provide a circular view with closing angles in the responsible sector no more than 0.5°;

b) have good visibility on the terrain at a distance of at least 1,000 m from them;

c) have convenient driveways that allow you to quickly take your places on the terrain, etc.

If we are talking about the use of means that can neutralize unmanned aerial vehicles, then it is appropriate to talk about the system of measures that must be carried out to protect strategically important objects from terrorist actions from the air, namely:

a) during the implementation of measures to protect strategically important objects, all flights of aircraft over the object must be prohibited;

b) aircraft or their debris, within the zone of neutralization by means of air defense, must not fall on the territory of strategically important objects;

c) for the placement of air defense means, it is necessary to have previously equipped places along the entire zone (perimeter) that is intended for protection, or – in the most threatening directions;

d) before making a decision on organizing the protection of strategically important objects from terrorist actions or air attack, it is necessary to assess the size of strategically important objects and the area around it.

In particular, the assessment of strategically important objects should involve the study of its character and geometric dimensions, the importance of its elements, vulnerability, hiddenness.

As a result of the assessment of strategically important objects, the most likely methods of actions of unmanned aerial vehicles, the directions of concentration of efforts, the order and methods of attacking strategically important objects and its elements are determined.

At the same time, the assessment of the terrain determines its general nature and impact on the possible actions of unmanned aerial vehicles, the conditions for their detection, especially at low and extremely low altitudes, the presence and condition of nearby roads, etc. In each specific case, these factors must be taken into account when building a system for protecting strategically important objects from aerial attacks.

The choice of locations on the terrain of air defense means is determined by their considerable number of conditions and limitations. In particular, the number of places for their placement is determined by:

$$n = \left\lfloor \frac{L}{d} \right\rfloor, \quad (1)$$

where L – the length of the zone (perimeter) that is intended for protection;
d – the distance between the locations of anti-aircraft defenses.

To protect strategically important objects from terrorist attacks from the air, air defense forces can be rotated. To perform tasks, it is advisable to schedule the rotation of these means. The development of a rotation schedule will solve the problems of regulating the operation of various air defense means, will help preserve the resource and will allow constant possession of information about the situation around strategically important objects.

It is considered necessary to develop a methodology for choosing the location of air defense means during the protection of strategically important objects from unmanned aerial vehicles (Fig. 1), which consists of procedures and tasks that are performed sequentially, as a result of which proposals for choosing locations are formed means of anti-aircraft defense (Shincaruk O. N., Kyrylenko V. A., Babii Y. A., Polishchuk V. V., Babaryka A. O., Chukanov A. I., 2020; Babii Yu., Chesanovskyi I., Levchunets D., 2016).

The initial data for calculating the distance between air defense means (block 1) are:

a) types of unmanned aerial vehicles that can be used for strategically important objects;

b) geographic coordinates of strategically important objects and their spatial dimensions;

c) composition of anti-aircraft defense equipment allocated for the protection of strategically important objects;

d) the maximum effectiveness of the use of air defense means.

Initial data are selected from prepared databases, which are formed in advance or in the process of preparing the solution (block 1).

In block 2, the area of the fall of the debris of unmanned aerial vehicles after its neutralization is calculated. To perform this task, an existing model is used (Sukharevsky O. I., 2014). The calculation of the area of the fall of the wreckage of unmanned aerial vehicles is carried out in order to determine the necessary removal distance of the locations of air defense means from the perimeter of strategically important objects.

Analysis of the results of modeling the neutralization of unmanned aerial vehicles at all possible flight speeds and altitudes showed that the removal distance of placements should be within 1 to 2 km from strategically important objects.

Among the boundaries determining the operation of air defense means, the most important place is occupied by the range of unmanned aerial vehicles from strategically important objects, during which the task of its disposal should be set.

This range depends on which air defense device is tasked, and on the flight height of the unmanned aerial vehicle of the neutralization zone outside the strategically important object. The horizontal distance from the strategically important object to the boundaries of setting tasks for neutralizing unmanned aerial vehicles is determined by the expressions:

$$d_{UAV} = d_{t.out.AD} + V_{UAV}(t_{DTr.UAV} + t_{neut.UAV}), \quad (2)$$

where d_{UAV} – the horizontal distance from the strategically important object to the boundary of setting tasks;

$d_{t.out.AD}$ – distance from the location of air defense equipment from a strategically important object;

V_{UAV} – the speed of the unmanned aerial vehicle;

$t_{DTr.UAV}$ – the time of direct preparation of anti-aircraft defense means to neutralize an unmanned aerial vehicle;

$t_{neut.UAV}$ – time for neutralization of the unmanned aerial vehicle at the border of the neutralization zone.

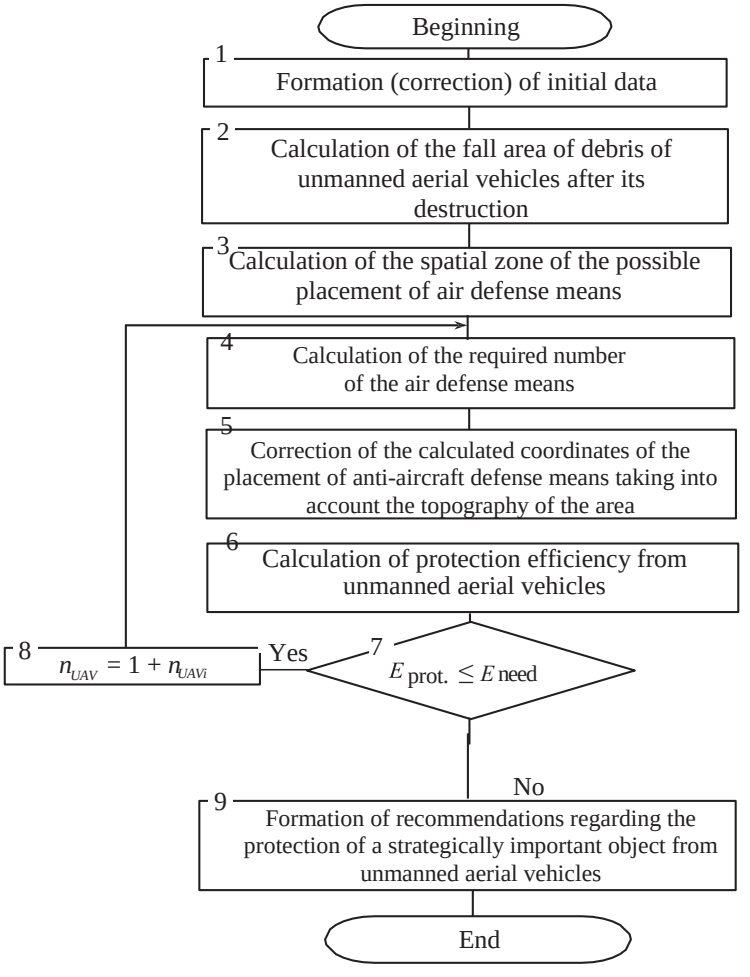


Figure 1. A structural and logical scheme of a methodical approach to the selection of the location of air defense means during the protection of a strategically important object from unmanned aerial vehicles

In block 3, the calculation of the spatial zone of the possible placement of air defense means is carried out. The wreckage of an unmanned aerial vehicle should not fall on a strategically important object, so the neutralization of an unmanned aerial vehicle should be carried out on average (depending on the type of unmanned aerial vehicle) at a distance of 2 km or more from a strategically important object.

In particular, the locations of anti-aircraft defense equipment must be moved beyond the territory of a strategically important object at a distance of 1 km or more. And the greater the distance of the placement of air defense means, the more the probability of preserving a strategically important object increases. On the other hand, the greater the distance of the location of air defense means from a strategically important object, the more means must be involved for its reliable protection. In practice, the number of anti-aircraft defenses that can perform tasks is limited (Horodnov V. P., 1987).

Therefore, it is necessary to place air defense facilities as close as possible to the strategically important object, guided by their characteristics and the number of air defense facilities allocated to protect the strategically important object. After obtaining the value of the necessary removal distance of the location of air defense means outside the strategically important object, the necessary number of them is calculated (block 4).

The next step is the implementation of the algorithm for correcting the calculated coordinates of the placement of anti-aircraft defenses based on the analysis of the digital terrain map (block 5).

If the terrain or the nature of the terrain creates obstacles for the placement of air defense means, then correction of their placement is carried out. The program of displaying anti-aircraft missile troops in accordance with the proposed locations on the electronic map is being implemented. For a more detailed and high-quality assessment of the placement of air defense means in block 6, an algorithm was implemented for assessing the degree of protection of a strategically important object from an unmanned aerial vehicle should be carried out on average (depending on the type of unmanned aerial vehicle.

The assessment of the degree of protection of a strategically important object is carried out in in the form of a calculation table showing the coefficients of the neutralization zones and the load coefficients of air defense means. Using this information (blocks 7–9) a final decision is made regarding the placement of air defense means.

In order to assess the impact of the compatibility of air defense and electronic warfare on the effectiveness of their actions, it is necessary to consider the meaning of the concept of “compatibility”, as well as to logically connect the concepts and terms related to the concept of “compatibility of air defense and electronic warfare” (Lezik V. O., 2015).

At the same time, the terminological system and its elements (terms) must have certain properties that are presented to it:

1. Systemic conditioning of terms, their interdependence, subordination according to a certain feature.
2. Unambiguity within military science and general science disciplines.
3. Context-independent term accuracy.
4. Correlation of the term with only one concept.
5. Shortness of the term and lexicographic approach to the creation of terms.
6. Terminology's ability to expand, clarify and change, the possibility of transition of the term to denote a generic concept.

Based on the listed requirements for terminology and the analysis of the existing main special terms, the “zone of joint actions of anti-aircraft defense and radioelectronic warfare” means the territory where they are located and the airspace where neutralization and radio electronic suppression of an unmanned aerial vehicle is carried out (Fig. 2).

Thus, the application of all possibilities related to the use of means in the zone of joint actions should be considered as a set of four constituent parts:

1. “Information interoperability of anti-aircraft defense and radioelectronic warfare” means the ability to carry out coordinated simultaneous actions of these means in the zone of joint duty.

2. “Compatibility regarding conditional neutralization of an unmanned aerial vehicle by means of air defense and electronic warfare” – as the ability to take coordinated actions on an unmanned

aerial vehicle in the zone of compatible actions of air defense and electronic warfare (Lezik V. O., 2015).

3. "Electromagnetic compatibility of the effective use of anti-aircraft defense and radio electronic warfare" means the ability of radioelectronic means to simultaneously function in real operating conditions with the required quality under the influence of unintentional radio interference and not to create unacceptable radio interference to other means.

4. "Compatibility for effectively changing the locations of anti-aircraft defense and radioelectronic warfare" – as the ability to simultaneously fold, move taking into account the passability of the means and place them in a new place.

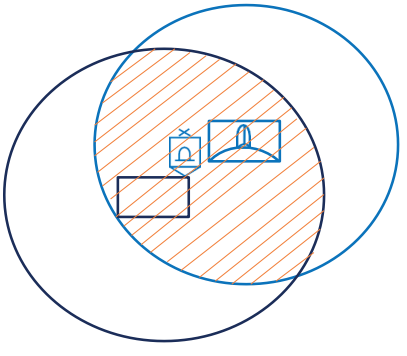


Figure 2. Zone of joint actions of air defense means and electronic warfare (indicated by a dotted line)

Results

The assessment of the effectiveness of the combined actions of air defense and radio electronic warfare as part of special means is intended to solve the scientific task, achieve the goal of the research and includes:

a) selection and substantiation of indicators of the effectiveness of the use of anti-aircraft defense and radio-electronic warfare;

b) a study of the dependence of the effectiveness of the combined actions of air defense and electronic warfare on formalized indicators of alternative options for the use of air defense.

The indicator of the quality of the result (effectiveness) of actions during the protection of a strategically important object is, in general, an m-dimensional vector that includes three groups of components: the achieved (expected) effect (g), time consumption (t) and resource consumption (c) and is described by the expression:

$$Y^m = [g^m, c^m, t^m], \tag{3}$$

Y^m – effectiveness of actions during the protection of a strategically important object;

m – factors and conditions that determine the effectiveness of actions during the protection of a strategically important object;

g^m – achieved (or expected) beneficial effect;

c^m – expenditure of resources;

t^m – waste of time.

We will consider ways to increase the effectiveness of protecting a strategically important object from an unmanned aerial vehicle due to the combined use of air defense and electronic warfare.

In general, the scientific task of researching the combined actions of anti-aircraft defense and radioelectronic warfare in the protection zone of a strategically important object is multivariate.

The number of options (n_{var}) depends on the number and types of these means and can be determined by the ratio:

$$n_{var} = (N_{ADMi} +1)(N_{ADMj} +1)(N_{nois.rad.interf.st.} +1)(N_{resp.-imp.radiointerf.st.} +1) \quad (4)$$

where N_{ADMi} – number of air defense means of the *i-th* type;
N_{ADMj} – number of air defense means of the *j-th* type;
$N_{nois.rad.interf.st.}$ – the number of noisy radiointerference stations;
$N_{resp.-imp.radiointerf.st.}$ – the number of response-impulse radiointerference stations.

The composition of anti-aircraft defense and radio-electronic warfare and the order of their deployment are mutually determined and closely interdependent. This relationship is caused, on the one hand, by those methodological approaches that exist to justify the optimal quantitative composition due to the necessary order of their placement, on the other hand, by the fact that any composition of means must be placed relative to the object of protection in a rational way (Lezik O. V., Ryazantsev S. S., Knysh D. V., 2015).

The effectiveness of joint actions depends both on the composition of the means and on the order of their placement, the parameters of which are the range of places of placement of air defense means ($d_{depl.ADM}$) and electronic warfare ($d_{depl..el.warfare}$) from the borders of the strategically important object and mutual distances between means of protection ($D_{ADM\text{-}EWF}$, D_{ADMi}, D_{EWFi}).

Thus, a rather complex nature of the dependence of the effectiveness of air defense and radio-electronic warfare measures is obtained, which can be presented in the form of a functional dependence:

$$\begin{aligned} E &= f\{N_{ADM}\} \mid N_{ADM}, d_{depl.ADM}, d_{depl.el.warfare}, D_{ADMi}, D_{EWFi}, D_{ADM\text{-}EWF} \mid = \text{const.} \\ E &= f\{N_{el.warfare}\} \mid N_{ADM}, d_{depl..el.warfare}, d_{depl.ADM}, D_{EWFi}, D_{ADMi}, D_{ADM\text{-}EWF} \mid = \text{const.} \end{aligned} \quad (4)$$

Locations of air defense and electronic warfare are subject to the requirements of the task, i.e. locations of air defense must be located at such a distance from the borders of a strategically important object that ensures the removal of the neutralization zone of the means abroad from which an attack by an unmanned aerial vehicle is possible. To assess the impact of the maximum effectiveness of the use of anti-aircraft defense and radioelectronic warfare on the effectiveness of their joint actions, let's return to the essence of the term “compatibility”.

The “zone of joint actions of the effective use of anti-aircraft defense and radio electronic warfare” means the territory where they are located and where neutralization and radio electronic suppression of unmanned aerial vehicles is carried out. The most adequate target assignment of air defense means during the protection of a strategically important object from an unmanned aerial vehicle is the indicator of the number of neutralized unmanned aerial vehicles from the total number of unmanned aerial vehicles that were involved in the attack.

In particular, with regard to the choice of indicators of the ratio of defense forces, the most complete confrontation of air defense means and unmanned aerial vehicles can reflect the ratio:

$$\partial_i = \frac{\text{NmaxUAV_ADMi} \times \lfloor 1-(1-\text{Pneutral.UAV_ADMi})^n \times \text{Ke.i.p.} \times N_{ADMi} \rfloor}{\text{Db.p.z.neutral ADMi} \times N_{UAV}} = \frac{\text{Kk.p.ADMi}}{N_{UAV}}, \quad (5)$$

where $N_{maxUAV_ADM_i}$ – the maximum number of unmanned aerial vehicles simultaneously neutralized by means of air defense of the *i-th* type;

$P_{neutral.UAV_ADM_i}$ – the probability of neutralizing unmanned aerial vehicles by means of air defense of the *i-th* type;

n – the number of missiles (resources) used to neutralize unmanned aerial vehicles;

$K_{e.i.p.}$ – efficiency ratio of information provision;

$D_{b.p.z.\ neutral\ ADM_i}$ – the limit parameter of the neutralization zone by means of anti-aircraft defense of the *i-th* type;

N_{UAV} – the number of unmanned aerial vehicles during an attack on a strategically important object;

$K_{k.p.\ ADM_i}$ – coefficient of the combat potential of air defense means of the *i-th* type.

Where $K_{e.i.p.}$ the coefficient of effectiveness of information provision is determined by the expression:

$$Ke.i.p. = \frac{Ksim.false.pl.tr. \times K_{Mask.}(1+N_{\Sigma n.prot.})N\Sigma n.prot.}{tt.st.ADM\ (1-ti.c.)}, \quad (6)$$

where $K_{sim.false.pl.tr.}$ – the coefficient of similarity of false placements to true ones;

$K_{Mask.}$ – the coefficient of the masking of a strategically important object;

$N_{\Sigma n.prot.}$ – the total number of forces and means of protection (air defense and electronic warfare) of a strategically important object against unmanned aerial vehicles that carry out disinformation measures;

$N_{\Sigma i.m.}$ – the total number of information means as part of air defense and electronic warfare protection of a strategically important object from unmanned aerial vehicles, information flows participating in the collection process;

$t_{t.st.\ ADM}$ – time of stay of anti-aircraft defense means at the location;

$t_{i.c.}$ – time of information collection.

The destruction of unmanned aerial vehicles during the protection of a strategically important object from the air is considered as a probabilistic process characterized, first of all, by the ratio of the forces of the parties.

To evaluate the effective use of radioelectronic warfare means for the protection of a strategically important object, the mathematical expectation of the number of unmanned aerial vehicles that have been affected by radioelectronic warfare (suppression) by means of radio electronic warfare is used ($M_{UAV\ c.out.ADM}$):

$$M_{UAV_c.out.ADM} = N_{UAV_c.out.} \times \Delta Psav.SIO \quad , \quad (7)$$

where $N_{UAV_c.out.}$ – the number of unmanned aerial vehicles on which radioelectronic influence (suppression) was carried out;

$\Delta P_{sav.\ SIO}$ – an increase in the probability of saving a strategically important object, which is equal to the probability of conditional neutralization of the unmanned aerial vehicle(s). It is determined by the dependence of the number of conditionally neutralized unmanned aerial vehicles and is calculated according to the formula:

$$\Delta P_{sav.}SIO = P^{P}_{sav.ob} - P^{V}_{sav.ob}, \quad (8)$$

where $P_{sav.ob}^{P}$ – the probability of preserving a strategically important object in the conditions of countermeasures against means of electronic warfare;

$P_{sav.ob}^{V}$– the probability of preserving a strategically important object in the absence of countermeasures against radioelectronic warfare.

For the case of protecting a strategically important object only by means of electronic warfare, expression (8) can be transformed into the form:

$$P_{sav.SIO} = 1 - e^{-N_{UAV_SIO} P_{sav.SIO}/N_{UAV}} \quad (9)$$

where $P_{sav.SIO}$ – the probability of preserving a strategically important object by means of radioelectronic warfare;

N_{UAV_SIO} – the number of unmanned aerial vehicles of a strategically important facility;

N_{UAV} – the number of unmanned aerial vehicles.

The analysis of the ratios shows that when assessing the effectiveness of joint actions, only the capabilities of anti-aircraft defense or the capabilities of radioelectronic warfare are taken into account with a fixed number of unmanned aerial vehicles participating in an attack on a strategically important object (Lezik O. V., Ryazantsev S. S., Knysh D. V., 2015).

Therefore, as a result of this property, it is proposed to transform the dependence into the form, which allows determining the efficiency indicator of compatible actions into the form:

$$P_i = 1 - e^{-\left(\frac{M_{destr.UAV_ADM}}{N_{л.а.}} + K_{comp.}\frac{M_{destr.UAV_SIA}}{N_{л.а.}} + K_{op.real.}\frac{M_{destr.UAV_l.alt.}}{N_{л.а.}}\right)}, \quad (10)$$

where $M_{destr.UAV_ADM}$ – mathematical expectation of the number of destroyed unmanned aerial vehicles by means of air defense;

$K_{comp.}$ – compatibility factor of anti-aircraft defense and radioelectronic warfare;

$M_{destr.UAV_SIA}$ – mathematical expectation of the number of destroyed unmanned aerial vehicles by means of electronic warfare;

$K_{op.real.}$ – coefficient of opportunity realization;

$M_{destr.UAV_l.alt.}$ – mathematical expectation of the number of destroyed unmanned aerial vehicles at low altitudes.

Figure 3. Mathematical model of protection effectiveness assessment strategically important object from the number of destroyed unmanned aerial vehicles by air defense forces

Based on the results of the analysis, it can be concluded that to evaluate the effectiveness of the joint actions of the air defense and radio electronic warfare units, a generalized indicator was chosen in the form of a mathematical expectation of the number of means (unmanned aerial vehicles) of air attack that did not complete the combat mission, defined in the relative value (P_i) and calculated by formula (10). Based on the value of this indicator, it is possible to evaluate the expected results of combat operations of air defense units and electronic warfare, the level of losses by means of air attack (unmanned aerial vehicles) and the degree of their performance of combat missions.

To deploy the variant of the combat composition of the air defense unit in battle order, a methodical technique was used for the directed selection of possible variants of the combat composition of the air defense unit within the framework of the existing organizational and personnel structure, with the conditional deployment of the air defense unit in battle order at fixed distances between “pairs” (anti-aircraft missile battery-electronic warfare unit) of a relatively strategically

important object (Lezik O. V., Ryazantsev S. S., Knysh D. V., 2015).

To implement this technique, we will use the ratio:

$$D_{UAI-SIAmin} - = a \times \text{J}, \tag{11}$$

where $D_{UAV-SIAmin}$ – the minimum range of anti-aircraft defense and radioelectronic warfare from the center of a strategically important object, in which their given number is evenly spaced at intervals of J;

a – uniformity factor.

For means of air defense and electronic warfare relative to each other and to a strategically important object, we use the ratio:

$$D_{UAI-SIAmin} = D_{detec.} \leq 0{,}65 D_{rec.rang.ammun.min}, \tag{12}$$

where $D_{detec.}$ – detection range;

$D_{rec.rang.ammun.min}$ – the minimum recoil range of the ammunition, which is determined from the expression:

$$D_{rec.rang.ammun.min} = V_{UAV} T_{f.t.ammun.} - \Delta + V_{UAV} T_{destr.UAV}\ , \tag{13}$$

where V_{UAV} – the speed of the unmanned aerial vehicle, km/min;

$T_{f.t.ammun.}$ – fall time of ammunitions using an unmanned aerial vehicle, min (or fall time of an unmanned aerial vehicle of the "Shahed-136/139", min);

Δ – ammunition lag using an unmanned aerial vehicle, km;

$T_{destr.UAV}$ – the time of destruction of the unmanned aerial vehicle.

In order for a strategically important object to be protected by means of radioelectronic warfare, it is necessary to place means of radioelectronic protection at a distance $D_{El.v.}$, which should be less $D_{ADM-El.v.min}$ or at best was equal to zero. At the same time, the reduction of the removal of places of placement of means of radioelectronic warfare ($D_{El.v.}$) is limited to the possibility of destroying a strategically important object when using a weapon that is self-guided by radioelectronic warfare radiation. A condition that determines the minimum and at the same time optimal value $D_{El.v.}$ looks like this:

$$D_{El.v.} \geq D_{destr.ammun.} + d_{SIO} + 3\sigma_{r.m.}\ , \tag{14}$$

where $D_{destr.ammun.}$ – radius of damage by munitions of a strategically important object;

d_{SIO} – the radius of a strategically important object;

$\sigma_{r.m.}$ – root mean square error of homing weapons.

The task of calculating the distance between the locations of air defense means during the protection of a strategically important object from unmanned aerial vehicles is determined by choosing the locations of air defense in two stages:

1. Proposals are being developed for the placement of air defense equipment in accordance with the requirements of the governing documents and the practice of organizing the protection of a strategically important object without taking into account the topography of the area (Lezik O. V., Ryazantsev S. S., Knysh D. V., 2015);

2. Correction of the coordinates of the placement of air defense means is carried out, taking into account the relief and nature of the terrain, the location of local objects that affect the effectiveness of the use of air defense forces to neutralize the unmanned aerial vehicle, using the capabilities of digital maps of the area.

Discussions

The conducted analysis showed that it is necessary to have pre-equipped locations of anti-aircraft defense and radioelectronic warfare along the entire zone (perimeter) that is intended for preservation, or in the most important directions. In each specific case, these factors must be taken into account when building a system to protect a strategically important object from an unmanned aerial vehicle. The developed proposals were elaborated in a comprehensive model for evaluating the effectiveness of air defense measures (Yermoshin M. O., 2004; Volkov A. F., Yanenko O. A., Kravchenko S. A., 2019).

Conclusion

Using the proposed method of choosing the location of air defense and electronic warfare during the protection of a strategically important object from the terrorist actions of an unmanned aerial vehicle, it is possible to develop such proposals, the use of which will ensure a high degree of protection of a strategically important object.

To evaluate the effectiveness of the combined actions of air defense and radioelectronic warfare, a generalized indicator was chosen in the form of a mathematical expectation of the number of unmanned aerial vehicles that did not complete a combat mission, defined as a relative value (W*i*), by the value of which it is possible to evaluate the results of the actions of air defense and radio electronic warfare, the level of losses of unmanned aerial vehicles and the extent of their tasks.

Recommendations

The materials of the article are of practical value for management bodies that, when planning the use of troops (forces), perform calculations to determine the required number of means of protection against unmanned aerial vehicles.

Further research in this direction will be aimed at developing a holistic methodology for evaluating the effectiveness of air defense forces, in particular, performing simulations that will allow to obtain estimates of the probability of preserving a strategically important object in the event of terrorist actions from the air by typical unmanned aerial vehicles at different heights (“Shahed-136/139”, “Orlan-10”, FPV, etc.).

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