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O. Rosliakov **S. Horielyshev**

COMPREHENSIVE MODEL OF COUNTERACTION AGAINST UNMANNED AIRCRAFT BY FORCES AND MEANSMILITARY UNIT ON THE PROTECTION OF AN IMPORTANT GOVERNMENT FACILITY (NUCLEAR INSTALLATION)

A comprehensive three-level model of countering unmanned aerial vehicles for the protection of nuclear installations by the National Guard of Ukraine is presented. The comprehensive model consists of three parts: a model of the buffer zone determination process, a model of unmanned aerial vehicles detection, and a model of their destruction and/or neutralization. For the first time, a method for calculating the buffer zone is proposed, taking into account the characteristics of unmanned aerial vehicles, response time, and reachable zones of mobile fire groups. The possibility of using bistatic radar in the early target detection zone is substantiated. The process of destroying unmanned aerial vehicles was modeled using a stochastic mass service system of the M/M/n/m type with exit from the queue. The results of the study make it possible to increase the effectiveness of the combat use of mobile fire groups in conditions of limited resources and adapt the defense system to modern threats.

Keywords: *unmanned aerial vehicles, nuclear installation, buffer zone, bistatic radar, mobile fire groups.*

Statement of the problem. In the period from 2022 to 2025, Ukraine is experiencing a rapid increase in the scale and intensity of the use of strike unmanned aerial vehicles (UAVs) by the enemy. If in 2022, kamikaze drone attacks were mainly single in nature, then in 2024–2025 they acquired a massive, wave and combined nature. Thus, in the first half of 2025, more than 22,500 attacks by Shahed-136/Geran-2 UAVs and their imitators were recorded [1], a significant part of which was directed at energy and critical infrastructure facilities, includingnuclear installations (Figure 1).

Traditional approaches to protecting nuclear facilities, which are based on the use of stationary means of detecting and intercepting high-speed air targets, have shown insufficient effectiveness against small-sized, low-visibility and low-altitude UAVs. An illustrative example is the incident at the Chernobyl NPP on February 14, 2025, when a kamikaze drone hit the protective shell of the Arch of the new safe confinement, causing a hole with a diameter of 6 m and damage to the crane system.

In response to new threats, mobile fire groups (MFGs) equipped with small arms, man-portable anti-aircraft missile systems (MANPADS), electronic warfare (EW) and detection equipment were created. However, the lack of a clear scientifically based approach to their deployment, coordination, definition of the area of responsibility and response time leads to a decrease in their effectiveness. In addition, the lack of a single integrated system that would combine radar stations (RALS), optoelectronic means, EW means and MFG in a spatio-temporal context does not allow an adequate response to complex, multi-vector attack scenarios.

Therefore, today there is a need to review the principles of organizing the protection system of nuclear facilities, taking into account new modern threats and resource limitations for their protection.

Analysis of recent research and publications. The publications closest in terms of issues to the defined research direction are [2–8]. In the articles [2, 3], a model of counteraction to UAVs is proposed, in which the probability of their detection is estimated, as well as the probability of destruction using a queue-based system with waiting and leaving the queue. At the same time, the model does not consider the multi-level counteraction structure and does not take into account the dynamics of threats in space and time.

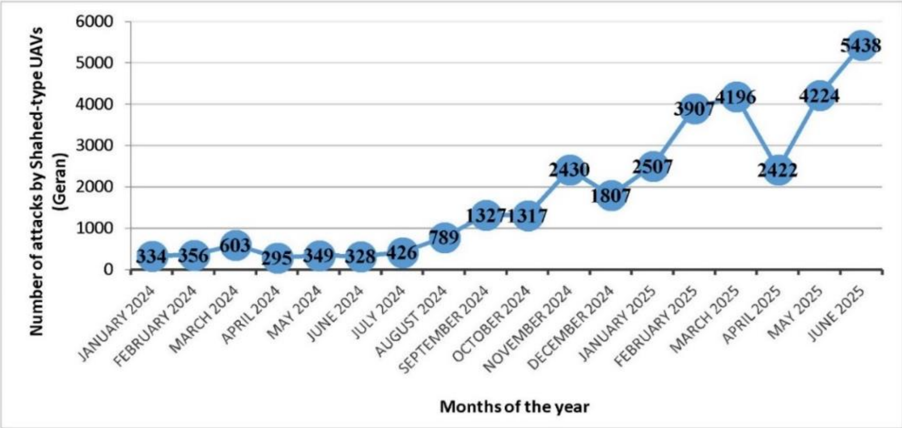

Figure 1 – Dynamics of attacks by unmanned aerial vehicles of the Shahed type (Geran) (Source developed by the authors based on [1])

In [4], a mathematical model of complex countermeasures against unmanned aerial vehicles based on the theory of Markov processes is presented. The model is built using a mass service model with heterogeneous service channels, which reflects the diversity of means of detecting and defeating UAVs. However, this model does not take into account the influence of technical characteristics of unmanned aerial vehicles, the deployment and response time of means of detecting and fire defeat, and geospatial constraints.

In the source [5] the main focus is on the development of a UAV countermeasure system, which includes detection (optical, acoustic, radar, radio monitoring), suppression (electronic warfare) and control subsystems. The article focuses on non-fire means (suppression and interception of control), but does not consider integration with fire means (anti-aircraft systems, large-caliber machine guns, small arms) or physical barriers (nets, protective domes), which are important for protecting NPP elements from kamikaze drones.

In the article [6], a model for assessing the effectiveness of an electronic warfare system against UAVs based on a probabilistic approach is considered. Despite the high level of detail of individual subsystems, the model does not take into account the spatio-temporal dynamics of air threats and does not integrate electronic warfare into the overall defense system of the facility.

The study [7] describes in detail modern active means of countering UAVs, but does not assess their effectiveness.

The paper [8] contains an important practical review of modern means of combating unmanned aerial vehicles, focusing on their characteristics and development prospects, but does not offer a structured model of countering UAVs. There is no analysis of the integration of electronic warfare and fire control means, taking into account their mutual overlap of areas of action to increase effectiveness.

Thus, the analysis of literary sources showed that the issue of implementing a comprehensive approach that combines quantitative modeling, modern detection methods, and adaptive response mechanisms depending on the type of threats and scenarios of the situation, as well as taking into account the available forces and means of military units, requires further research.

The purpose of the article is the development of a comprehensive model for countering unmanned aerial vehicles by the forces and means of a military unit protecting an important state facility (nuclear facility).

Summary of the main material. According to combat experience, a UAV defense system should be comprehensive and contain at least three consecutive stages: detection, suppression, and destruction of targets [9].

The authors of the article propose a UAV countermeasure system for the military unit for the protection of nuclear installations, which has a three-level structure (Figure 2). The first level (10–50 km) involves early detection of targets using radar, IR cameras, acoustic sensors and external target designation sources (for example, "Virazh tablet", AeroScope). The second level (3–10 km) is implemented by electronic warfare means, in particular by GPS/GNSS suppression systems and control channels, as well as anti-drone rifles.

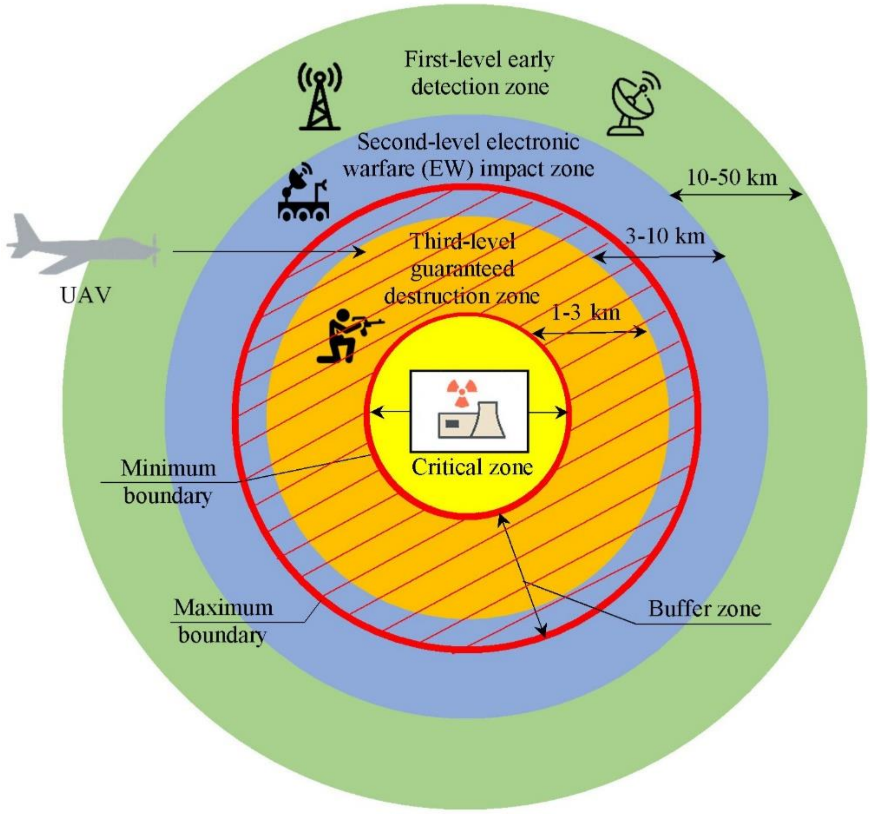

Figure 2 – Graphic diagram of the organizational structure of the system for countering unmanned aerial vehicles

The third level (1–3 km) is aimed at guaranteed destruction of UAVs with small arms, anti-aircraft weapons and MANPADS. The effectiveness of the defeat depends on the accuracy of detection, the choice of the point of fire contact and the characteristics of the means of destruction.

In order to predict the likelihood of counteraction to UAVs by the forceSs and means of the military unit of the National Guard of Ukraine in the specified areas A comprehensive model of countering UAVs by the forces and means of a military unit protecting an important state facility (nuclear facility) has been developed (Figure 3).

Within this UAV countermeasure system, one of the proposed elements is the buffer zone (Figure 2). It covers the space between the maximum and minimum response limits and defines the area within which the UAV must be detected, classified and neutralized before it enters the critical area of the facility. The buffer zone integrates the first and second level means of the system (detection and electronic warfare) and creates conditions for the effective use of mobile fire groups within the limited response time.

The parameters of the buffer zone are determined using analytical expressions (1) – (9) of block 1 (Figure 3). In particular, the minimum boundary $R_{\min}^{hit}$ is defined as the sum of the UAV's fall range D_{fall}^{UAV} after exposure to damaging factors and the maximum radius of destruction by the warhead R_{hit}^{UAV} after the UAV falls [expression (1)]. Falling range D_{fall}^{UAV} is calculated by expression (2) and is considered for two cases:

1) loss of controllability after the action of electronic warfare, which depends on the aerodynamic quality coefficient of the UAV K_{plan}^{UAV} and altitude of loss of control H^{UAV} [expression (3)] [10];

2) hitting a UAV with firepower, which depends on the speed of the UAV V^{UAV}, initial velocity of the fragments V_0, flight altitude, debris departure angles θ, aerodynamic drag, shape and mass of fragments [expression (4)] [11, 12].

1. A model of the process for determining the dimensions of a buffer zone for protecting a nuclear power plant from unmanned aerial vehicles:

$$R_{\min}^{hit} = D_{fall}^{UAV} + R_{hit}^{UAV}, \quad (1)$$

$$D_{fall}^{UAV} = \max\left\{D_{plan}^{UAV}, D_{hit}^{UAV}\right\}, \quad (2)$$

$$D_{plan}^{UAV} = K_{plan}^{UAV} \cdot H^{UAV}, \quad (3)$$

$$D_{hit}^{UAV} = V_x \cdot t_{fall}^{UAV}, \quad V_x = V^{UAV} + V_0 \cos\theta \quad (4)$$

$$R_{hit}^{UAV} = k_{hit} \cdot \sqrt[3]{m_{hit}^{UAV}}, \quad (5)$$

$$R_{\max}^{hit} = d_{p.MFG} + d_{h.MFG} + V^{UAV} \cdot T_{reactMFG}, \quad (6)$$

$$T_{reactMFG} = T_{CR} + T_{mov} + T_{prep}, \quad (7)$$

$$P_{arr}^{UAV} = 1 - e^{-\frac{T_{req}}{T_{reactMFG}}}, \text{ at } T_{reactMFG} \le T_{req}, \quad (8)$$

$$L_{buff} = R_{\max}^{hit} - R_{\min}^{hit}. \quad (9)$$

2. Unmanned Aerial Vehicle Detection Model:

$$P_{\text{detect}} = f\left(SNR, R, \sigma, S(\omega), \gamma, \lambda\right), \quad (10)$$

$$P_{rec} = \frac{P_{tr} G_{tr} G_{rec} \lambda^2 \sigma}{(4\pi)^3 R_{tr-UAV}^2 R_{UAV-rec}^2 L}, \quad (11)$$

$$SNR = \frac{P_{rec}}{P_n} = \frac{P_{tr} G_{tr} G_{rec} \lambda^2 \sigma}{(4\pi)^3 R_{tr-UAV}^2 R_{UAV-rec}^2 L k T_0 B F_n}, \quad (12)$$

$$P_{\text{detect}} \approx Q_m\left(\sqrt{2 \cdot SNR}, \sqrt{-2\ln(F)}\right), \quad (13)$$

$$F = \exp\left(-\frac{h^2}{2\sigma_z^2}\right), \quad (14)$$

$$Q_m(a,b) = \int_b^\infty x \cdot \exp\left(-\frac{x^2 + a^2}{2}\right) \cdot J_{m-1}(ax)\,dx, \quad (15)$$

$$P_{\text{detect}} \approx 1 - \exp\left(-\frac{SNR}{\alpha \cdot SNR_0}\right), \quad (16)$$

$$\left(R_{\text{detect}}^{UAV}\right)_{\max} = \left(R_{tr-UAV} R_{UAV-rec}\right)_{\max} = \sqrt{\frac{P_{tr} G_{tr} G_{rec} \lambda^2 \sigma}{(4\pi)^3 (SNR)_{\min} P_n L}}, \quad (17)$$

$$\varepsilon_{clos} = \text{arctg}\left(\frac{h_v - \frac{D^2}{16,97} - (h_0 + h_{cn})}{D}\right), \quad (18)$$

$$\varepsilon_{UAV} = \text{arctg}\left(\frac{h_v + h_{UAV} - \frac{D^2}{16,97} - (h_0 + h_{obs})}{D}\right), \quad (19)$$

$$D_{act.vis} = k_{tr} \cdot D, \quad (20) \qquad D_{\text{detect}}^{TC} = \frac{L}{\theta_{\min}}, \quad (21)$$

$$\theta_{\min} \approx 1,22 \cdot \frac{\lambda}{D_l}, \quad (22)$$

$$P_{\text{detect}} = 1 - \exp\left(-\frac{(SNR)^2}{2 \cdot (SNR_0)^2}\right), \quad (23)$$

$$P_{\text{detect}}^{UAV} = 1 - \prod_{i-1}^{n}\left(1 - P_{\text{detect }i}\right). \quad (24)$$

3. Model of the process of destruction and/or neutralization of unmanned aerial vehicles:

$$\lambda = \frac{N_{UAV}}{T_{buff}}, \quad (25) \qquad T_{buff} = \frac{R_{\max}^{hit} - R_{\min}^{hit}}{V^{UAV}}, \quad (26)$$

$$\mu = \frac{1}{t_j}, \quad (27) \qquad \nu = \frac{1}{T_{buff}}, \quad (28)$$

$$P_0 = \frac{1}{\sum_{k=0}^{n} \frac{\rho^k}{k!} + \frac{\rho^n}{n!} \cdot \sum_{i=1}^{m} \frac{\rho^i}{\prod_{s=1}^{i}(n + s\beta)}}, \quad (29)$$

$$P_k = \frac{\rho^k}{k!} \cdot P_0, (0 < k \le n), \quad (30)$$

$$P_{destr}^{UAV} = \frac{1}{\rho}\left(n - \sum_{k=0}^{n}(n-k) \cdot P_k\right), \quad (31)$$

$$P_{count}^{UAV} = P_{detect}^{UAV} \cdot \left(P_{destr}^{UAV} + P_{EW}^{UAV} - P_{destr}^{UAV} \cdot P_{EW}^{UAV}\right). \quad (32)$$

Figure 3 – Structural diagram of a comprehensive model of countering unmanned aerial vehicles by the forces and means of the military unit protecting an important state facility (nuclear installation)

Radius of damage by the UAV warhead R_{hit}^{UAV} after falling, which depends on the mass of the explosive m_{hit}^{UAV} and empirical coefficient k_{hit}, is determined by the empirical formula (5) [13].

In the Excel software environmentthe dependences of the minimum threshold value were obtained $R_{\min}^{hit}$ from various tactical and technical characteristics (TTC) of the UAV (altitude, speed, warhead mass, etc.). For example, Figure 4 shows the dependences $R_{\min}^{hit}$ from the flight altitude for different UAVs.

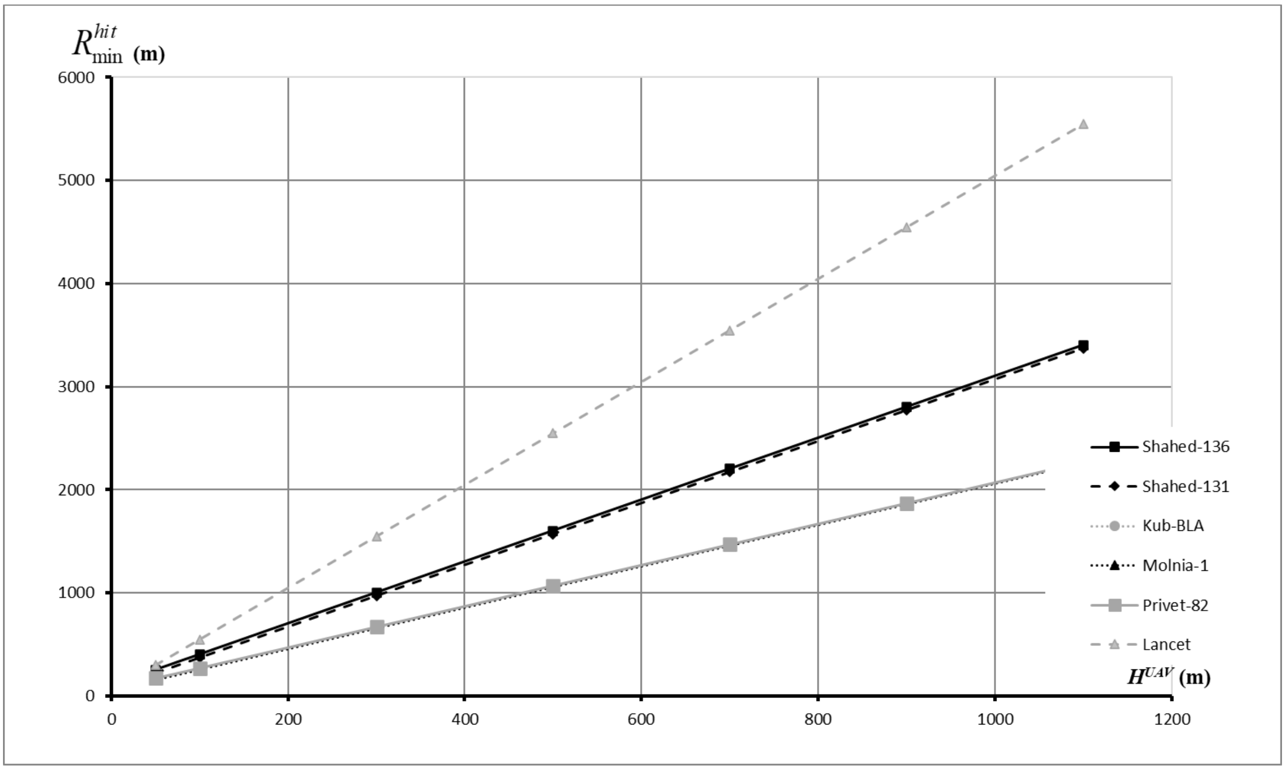

Figure 4 – Dependence of the minimum boundary range on flight altitude for various unmanned aerial vehicles

Maximum buffer zone boundary $R_{\max}^{hit}$ (Figure 5) is determined by expression (6). Its value depends on the range of damage with the available fire weapons of the MFG $d_{p.MFG}$, spatial arrangement of firing positions $d_{h.MFG}$, air target speed V^{UAV} and hace of MFG reaction $T_{reactMFG}$.

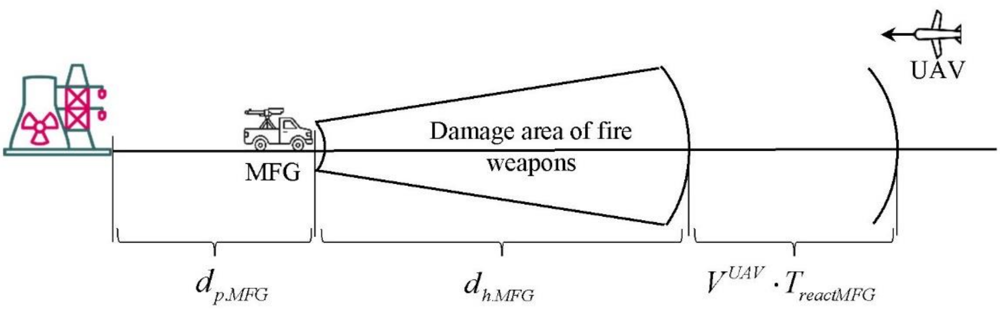

Figure 5 – Scheme for determining the maximum boundary ($R_{\max}^{hit}$) buffer zone of the nuclear power plant protection

MFG reaction time $T_{reactMFG}$ [expression (7)] this is the total combat readiness time T_{CR}, moving to a firing position T_{mov} preparation for shooting T_{prep}. In this case, the probability of successful preparation of the MFG P_{arr}^{UAV} to hitting the target after its detection [expression (8)] will depend on the time of the UAV's arrival T_{req} to the maximum limit $R_{\max}^{hit}$ and MFG reaction time $T_{reactMFG}$.

Determining the boundaries of the buffer zone of protection creates the basis for spatial planning of the actions of the air defense unit of the military unit for the protection of nuclear power plants regarding protection against UAVs. However, an effective response is only possible if air threats are detected early, even before the UAV enters this zone. One of the promising areas is the use of mobile bistatic radar systems (BRLS) for target detection (Figure 6), which use external illumination signals (FM, DVB-T, GSM, etc.) [14, 15].

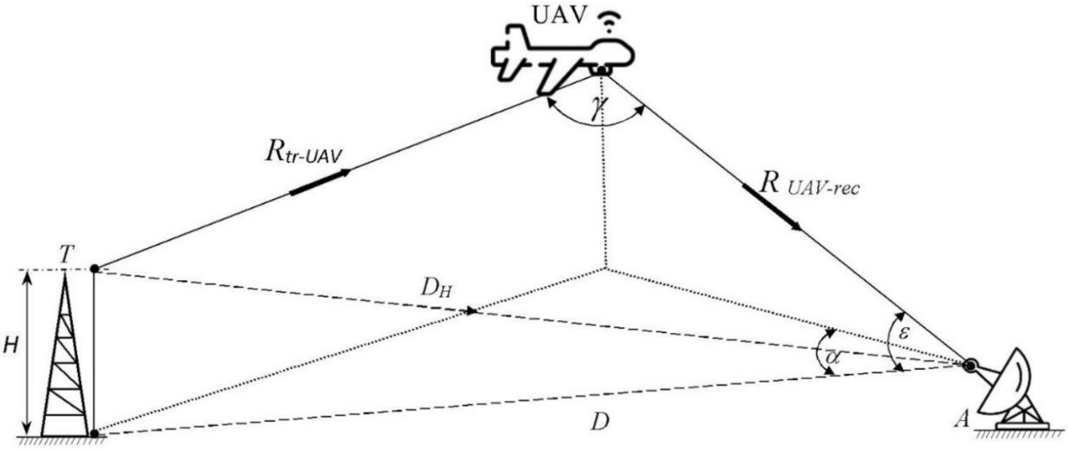

Figure 6 – Geometry of bistatic radar of unmanned aerial vehicles:
A– receiving antenna; *T* – transmitting antenna; $R_{UAV\text{-}rec}$ – distance from the UAV to the receiving antenna; $R_{tr\text{-}UAV}$ – distance from the transmitting antenna to the UAV; *D* – distance from the receiving antenna to the transmitting antenna (base); D_H – line-of-sight range; α – UAV azimuth, measured from the base; ε – UAV elevation angle, measured from the horizon; γ – bistatic angle

Thus, one of the key places in the The main advantages of this approach are stealth, low cost, use of existing radiation sources, the ability to create a coverage area of the required configuration, and the ability to deploy quickly in the field. These factors determine the feasibility of using radar to detect UAVs during the protection of critical infrastructure, in particular nuclear power plants. In addition, when deploying the detection position so that the target is between the transmitter and receiver (i.e. $\gamma \approx 180°$), one can expect an improvement in the detection probability due to the increased bistatic effective scattering surface (ESS), especially when using shorter waves (higher frequencies) [16].

Probability of detection P_{detect} [expression (10)] depends on the resolution, energy characteristics of the backlight source (P_{tr}, G_{tr}, λ), geometry of the system placement (R, γ), target speeds V^{UAV}, its EPR σ, interference, spectral characteristics of the signal $S(\omega)$ and the time the object stays in the detection zone.

Mathematical expressions (11)–(17) of block 2 (Figure 3) allow us to estimate the power of the received signal P_{rec} signal-to-noise ratio SNR, probability of detection P_{detect} and the maximum range of the system $\left(R^{UAV}_{\text{detect}}\right)_{\max}$ depending on the characteristics of the transmitter, receiver, signal type and target parameters [17–20]. To increase the efficiency of decision-making, the model also provides for the use of exponential approximation of the detection probability [expression (16)], which simplifies calculations in real time. Target detection in the bistatic channel makes it possible to form a sector of probable approach of the UAV and further refine the calculation of the minimum boundary and visibility zone for the positions of the MFG.

The locations of the MFG should be located outside the NPP at a distance not less than the minimum boundary. As this distance increases, the probability of preserving the facility increases, but so does the need for greater resources. With limited resources, the task of placing the MFG as close to the perimeter as possible, taking into account the available means, arises [21]. In this regard, for the rational placement of MFG, it is necessary to calculate the direct visibility zones taking into account the performance characteristics of optical, optoelectronic and visual means, relief and weather conditions. The determination of the direct visibility zone from the location of the MFG is carried out by the graph-analytical method using geoinformation systems (for example, the software complex "Kropiva", the information and communication system "DELTA", etc.). When solving this problem [expressions (18), (19)] using the angles of closure (ε_{clos}) and UAV sighting (ε_{UAV}) determines the maximum range of UAV detection by MFG personnel [22].

Weather conditions are taken into account by the atmospheric transparency coefficient k_{tr} [22], which corrects the actual visibility range $D_{act.vis}$ [expression (20)]. Detection range D^{TC}_{detect} adjusted according to the technical characteristics of the optoelectronic devices (minimum angular resolution $\theta_{\min}$, lens diameter D_l) and depends on the size of the UAV L [expressions (21), (22)]. The positions of the MFG are determined by the criterion $D_{act.vis} \le D^{TC}_{\text{detect}}$, which guarantees the probability of detecting a UAV by optoelectronic means, taking into account nonlinear noise statistics and the threshold signal-to-noise ratio SNR_0 necessary to achieve $P_{detect} = 0.5$, as well as the overlap of each point of space along a given boundary with at least one MFG.

Overall probability of detecting a UAV P^{UAV}_{detect} in the case of using several independent means (bistatic, opto-electronic, visual) it is calculated by formula (24).

Block 3 considers the process of destroying and/or neutralizing UAVs by the forces and means of the military unit for the protection of the NPP. The use of fire weapons (air defense, small arms, etc.) is carried out mainly within a predetermined zone of guaranteed destruction or partially in a buffer zone. Since the fire weapons of the MFG are limited in quantity, and the arrival of UAVs is random, the model is described by a mass service system (of the M/M/n/m type with exit from the queue) with a Poisson input flow (M) with intensity λ, which is defined by expression (25), exponential service time (M) [expression (26)], n channels, and a bounded queue of size m, which describes the number of UAVs that can be simultaneously in the affected area.

The process of destroying a single UAV has an exponential distribution with intensity μ, which is determined by expression (27). The opposite process of missing the target, i.e. the UAV carries out an attack or becomes unavailable for destruction, occurs with intensity ν [expression (28)].

Stateful goal service model graph S_j (j = 0, …, m), where j is the number of targets in the system, is shown in Figure 7.

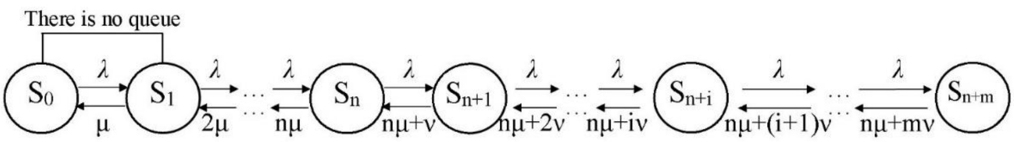

Figure 7 – State graph of the air target servicing model

In order to determine the probabilities of the states of the service model, we use expressions (29), (30), where $\rho = \frac{\lambda}{\mu}$, $\beta = \frac{\nu}{\mu}$ – channel loading coefficients and queue abandonment by targets, respectively. Probability of successfully destroying a UAV P^{UAV}_{destr} fire means, the MFG is calculated using expression (31) [2].

The developed comprehensive model for countering UAVs assumes that, along with fire weapons, the protection system for important state facilities, in particular nuclear power plants, includes electronic warfare means. Then the overall probability of neutralizing a UAV in a defense system should be considered as a combination of three probabilities: the overall probability of successfully detecting a UAV – P^{UAV}_{detect}; average probability of suppression of UAV onboard systems by electronic warfare means – P^{UAV}_{EW}; the probability of successful destruction of a UAV by fire weapons of the MFG – P_{destr}^{UAV} .

Since the use of both electronic warfare and fire damage is possible only after the target is detected, the final probability of successful counteraction of the UAV P_{count}^{UAV} by the forces and means of the military unit defending the nuclear installation is calculated using expression (32).

Conclusions

The article develops a comprehensive model of countering unmanned aerial vehicles by the forces of the National Guard of Ukraine during the defense of a nuclear installation, which makes it possible to: determine the boundaries of the buffer zone depending on the characteristics of air targets; optimize the placement of mobile fire groups; assess whether the MFG means are sufficient to counter the expected flow of unmanned aerial vehicles; determine the critical number of UAVs at which the system is overloaded (high intensity of exit from the queue); adequately model the process of combat use of fire weapons of mobile fire groups in the buffer zone of the NPP, taking into account the probabilistic nature of the arrival of targets, limitations of fire capabilities, as well as the critical time interval during which effective neutralization of targets is possible.

Unlike existing models [2, 4, 6], the developed complex model takes into account the use of mobile fire groups with the determination of their location, using the approach of overlapping visibility zones using GIS and early detection systems using mobile bistatic radars.

A promising direction for further research is the development of a method for assessing the capabilities of military units of the National Guard of Ukraine in the defense of nuclear installations, taking into account the developed comprehensive model of countering unmanned aerial vehicles.

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О. В. Росляков, С. А. Горєлишев

КОМПЛЕКСНА МОДЕЛЬ ПРОТИДІЇ БЕЗПІЛОТНИМ ЛІТАЛЬНИМ АПАРАТАМ СИЛАМИ ТА ЗАСОБАМИ ВІЙСЬКОВОЇ ЧАСТИНИ З ОХОРОНИ ВАЖЛИВОГО ДЕРЖАВНОГО ОБ'ЄКТА (ЯДЕРНОЇ УСТАНОВКИ)

Подано комплексну трирівневу модель протидії безпілотним літальним апаратам силами військової частини Національної гвардії України під час здійснення оборони ядерної установки, що складається з етапів виявлення, радіоелектронної протидії та вогневого ураження. Основним елементом моделі є буферна зона, що охоплює простір між максимальним і мінімальним рубежами реагування й визначає область, у межах якої мають бути забезпечені виявлення, класифікація та знешкодження безпілотних літальних апаратів до його входження у критичну зону об'єкта. Наведено математичний апарат для визначення параметрів буферної зони з урахуванням характеристик безпілотних літальних апаратів (висота, швидкість, бойове навантаження) і засобів протидії. Зокрема, враховано інерційне планерування дронів після ураження, розльот уламків, радіус ураження бойовою частиною.

Особливу увагу приділено інтеграції мобільних бістатичних радіолокаційних засобів виявлення, які використовують зовнішні сигнали підсвічування (FM, DVB-T, GSM) і забезпечують раннє виявлення цілей. У разі розгортання позиції виявлення так, щоб ціль знаходилася між передавачем і приймачем (тобто $\gamma \approx 180°$), можна очікувати поліпшення імовірності виявлення внаслідок підвищеної бістатичної ефективної поверхні розсіювання, особливо під час використання коротших хвиль (вищих частот). Розглянуто методику просторового аналізу зон видимості із використанням ГІС-інструментів для оптимального розміщення мобільних вогневих груп.

Запропоновано стохастичну модель типу M/M/n/m з виходом із черги, що відображує випадковість надходження безпілотних літальних апаратів, обмеженість засобів протиповітряної оборони та часові обмеження на їхнє знищення. Ця модель дає змогу визначити ймовірність пропуску БПЛА за умов масової атаки. Імовірність успішної протидії визначається як комбінація імовірностей виявлення, дії радіоелектронної боротьби та фізичного знищення, причому РЕБ дає можливість знизити ймовірність прориву ще до входу безпілотних літальних апаратів у буферну зону.

Розроблена комплексна модель протидії безпілотним літальним апаратам уможливить оцінку ефективності системи захисту об'єкта, визначення критичної кількості цілей, за якої система перевантажується, а також підвищення ефективності використання сил і засобів Національної гвардії України під час захисту ядерних об'єктів.

Ключові слова: *безпілотні літальні апарати, ядерна установка, буферна зона, бістатична радіолокація, мобільні вогневі групи.*

Rosliakov Oleksii – Adjunct, National Academy of the National Guard of Ukraine
https://orcid.org/0000-0001-9211-562X

Horielyshev Stanislav – Candidate of Technical Sciences, Associate Professor, Leading Researcher of Scientific and Research Center, National Academy of the National Guard of Ukraine
https://orcid.org/0000-0003-1689-0901