UDC 004.7:623.55.02
DOI https://doi.org/10.32782/msd/2024.1/05

METHOD FOR VERIFICATION OF ARTILLERY FIRING UNDER THE INFLUENCE OF RANDOM DISTURBANCES

Maksymov M. V.
Doctor of technical sciences, professor,
chief researcher of the research department,
scientific research center of the Armed Forces of
Ukraine «State Oceanarium» of the Institute of
the Naval Forces.
ORCID ID: 0000-0002-3292-3112

Gultsov P. S.
Master of Science, graduate student, Department
of Software and Computer-Integrated Technologies,
Odessa Polytechnic National University
ORCID ID: 0000-0001-5083-380X

Boltenkov V. O.
PhD in Engineering Sciences, Associate Professor of
the Information System Department,
Odessa Polytechnic National University
ORCID ID: 0000-0003-3366-974X
Scopus Author ID: 8575846900

Maksymov O. M.
Master of Science, Senior Researcher of the research
department, scientific research center of the Armed
Forces of Ukraine «State Oceanarium» of the Institute
of the Naval Forces
ORCID ID: 0000-0003-2504-0853

Random disturbances are always present in artillery firing. These disturbances cannot be eliminated during the preparation for firing. In practice, they are compensated for by consecutive shooting adjustment. Modern counter-battery tactics require minimizing the time of artillery units' firing exposure. Such tactics are the only way to preserve the combat capability and existence of the artillery units. In this regard, methods for verifying each artillery shot are very relevant. Verification is understood as confirming the effectiveness of the shot immediately after it is made. Verification as an assessment of the error in the coordinates of the projectile's burst can be carried out using optical or radar observation, or sound reconnaissance systems. However, the use of additional means is not always possible and effective. In this regard, verification methods based on the analysis of acoustic fields generated by firing are promising. Progressive information technologies are used for such analysis. A method for verifying the shot with the registration of the ballistic wave created by a projectile flying along a ballistic trajectory at supersonic speed is proposed. The signal of the ballistic wave is recorded by a distributed system of acoustic sensors located along the firing line. Based on the moments of arrival of the ballistic wave registered by the sensors, a system of approximating parabolas is constructed. The solution of the system allows for the determination of the expected point of the projectile's burst before it lands. The deviation of the burst point from the aiming point verifies the quality of the artillery shot. Simulation modeling of the proposed method has been carried out. It is demonstrated that parabolic approximation effectively compensates for random disturbances in firing. A comparison of the proposed method with the method of disturbance compensation by consecutive shooting adjustment has been conducted. It is shown that the proposed method significantly reduces the time of firing exposure of the weapon and the expenditure of projectiles to hit the target. The effectiveness of the verification method is confirmed by natural field testing.

Key words: *artillery shot, random disturbances, information technology, ballistic wave, parabolic approximation.*

Максимов М. В., Гульцов П. С., Болтьонков В. О., Максимов О. М. МЕТОД ВЕРИФІКАЦІЇ АРТИЛЕРІЙСЬКОГО ВИСТРІЛУ ПІД ЧАС ВПЛИВУ ВИПАДКОВИХ ЗБУРЕНЬ

В артилерійському пострілі завжди присутні випадкові збурення. Ці збурення не можна усунути в процесі підготовки стрільби. Традиційно вони компенсуються шляхом послідовної пристрілки. Сучасна тактика контр-

батарейної боротьби потребує максимального скорочення часу вогневого прояву артилерійського підрозділу. Лише така тактика дає змогу зберегти боєздатність та саме існування артилерійського підрозділу. У цьому плані дуже актуальні методи верифікації кожного артилерійського пострілу. Під верифікацією розуміється підтвердження ефективності пострілу одразу після його здійснення. Верифікація як оцінка помилки координат розриву снаряда може здійснюватися із застосуванням засобів оптичного чи радіолокаційного спостереження або систем звукової розвідки. Однак застосування додаткових засобів не завжди можливе та ефективне. У цьому плані перспективними є методи верифікації, засновані на аналізі акустичних полів, що виникають під час пострілу. Для такого аналізу використовуються прогресивні інформаційні технології. Запропоновано метод верифікації пострілу з реєстрацією балістичної хвилі, що створюється снарядом, який летить по балістичній траєкторії з надзвуковою швидкістю. Сигнал балістичної хвилі реєструється розподіленою системою акустичних сенсорів, що розташовані на лінії стрільби. На підставі зареєстрованих сенсорами моментів приходу балістичної хвилі будується система апроксимуючих парабол. Рішення системи дає змогу визначити очікувану точку розриву снаряда ще до його приземлення. Оцінкою відхилення точки розриву від точки прицілювання верифікується якість артилерійського пострілу. Проведено імітаційне моделювання запропонованого методу. Продемонстровано, що параболічна апроксимація дає змогу ефективно компенсувати випадкові збурення пострілу. Проведено порівняння запропонованого методу з методом компенсації збурень шляхом послідовного пристрілювання. Показано, що запропонований метод дає змогу істотно скоротити час вогневого прояву гармати та витрати снарядів на поразку цілі. Працездатність методу верифікації підтверджена натурною польовою перевіркою.

Ключові слова: *артилерійський постріл, випадкові збурення, інформаційна технологія, балістична хвиля, параболічна апроксимація.*

Introduction. Large-caliber field artillery has been and remains the main strike force in ground military operations [1]. According to [2], in 2022 the Armed Forces of Ukraine fired an average of 4,000–7,000 artillery shots per day, while from the Russian side this figure was 2-4 times higher. The use of artillery in local armed conflicts of the 21st century and during the Russo-Ukrainian war demonstrated that effective use of artillery is possible only based on new tactical models. The classic concept of counter-battery warfare [3] has today transformed into the «shoot-and-scoot» tactic [4]. An artillery unit's ability to strike the enemy while preserving its combat capability is possible only by reducing the time to hit the target to the minimum [5]. Each shot from an artillery installation gives the enemy an opportunity to estimate its coordinates and open return fire. Thus, the development of methods for conducting artillery fire, which allows completing the task of hitting the target with a minimum number of shots, is highly relevant.

The modern principles of increasing the accuracy of artillery firing are closely linked with the use of progressive information technologies (IT). IT today forms the basis for the compilation of firing tables (TC) [6]. The calculation of projectile flight trajectories using refined ballistic models is also based on the use of IT for accelerated assessment and prediction of firing accuracy in field conditions [7,8]. Special-purpose geographic information systems form the basis for the construction of map-tablets for artillery commanders [9, 10]. The further discussion of the important scientific and practical task of assessing the impact of random disturbances on firing accuracy will also be associated with the corresponding information technology.

Review of research sources. Modern means of ensuring the accuracy of artillery firing and current accuracy assessment, guidance methods, and adjustment can be divided into the following technological directions:

(i) – preliminary preparation for firing [11,12];

(ii) – verification of firing results, i.e., confirmation of the projectile hitting the target point or assessing the deviation from the aiming point [13].

The technological direction (i) is aimed at fully accounting for possible firing errors, mainly systematic, and includes:

- reconnaissance and determination of target coordinates;
- topogeodetic preparation;
- meteorological preparation;
- ballistic preparation;
- technical preparation;
- determining settings for firing.

Despite the constant improvement of the means of technological direction (i) and, in particular, the applied IT, random disturbances associated with the following factors, which are difficult to assess, can exist during firing:

– wear of the barrel of the artillery installation that occurred after its last measurement;

– heating of the barrel as a result of intense preceding firing;

– inaccurate information about the charge and its storage method.

Errors in firing due to the action of random disturbances require assessment during verification.

The technological direction (ii) is associated with establishing informational feedback between consecutive shots from an artillery installation [16, 17]. After each shot, a correction of the initial firing settings for the next shot is made. According to [17], the procedures for informational feedback are divided into two categories – «shoot-look-shoot» (SLS) for targets observed from the firing position, or «shoot-adjust-shoot» (SAS) for concealed firing positions. In both cases, the assessment of the coordinates of the projectile burst during firing is required, which significantly complicates and prolongs the verification procedure.

The most commonly used technologies for direction (ii) as of today are:

1. Optical observation, including the use of unmanned aerial vehicles (UAVs) [18,19]. Drawbacks include the demasking of the observation process and the vulnerability of observation means.
2. Determination of the projectile's landing point by artillery radar [20,21]. Drawback – demasking of the observation process due to radar radiation.
3. Processing of sound signals from projectile bursts, i.e., the use of sound reconnaissance means for artillery in the «Service of Own Firing» mode [22]. Drawbacks include the need for large spatially distributed sensor systems, and strong dependence of efficiency on weather conditions.

Let's look in more detail at the means of analyzing artillery acoustic fields. During artillery firing, two types of waves are formed. The sound pulse generated by the powder gases exiting the barrel directly behind the projectile forms a wave called the muzzle wave [18]. A wave similar in acoustic characteristics arises during the projectile's burst. This type of wave is the object of analysis in sound reconnaissance for artillery [23]. Another type of wave during firing is the air shock wave, generated by the movement of the projectile at supersonic speed and called the ballistic wave [24]. The ballistic wave remains a shock wave for as long as the projectile continues to move at supersonic speed and moves along with the projectile. The acoustic signal of the ballistic wave is an N-shaped pulse lasting 2 to 5 ms, with a wideband energy spectrum lying in the frequency range from 10 Hz to 500-700 Hz. The ballistic wave can only be registered within the Mach cone formed by a projectile flying at supersonic speed. For over 100 years in artillery sound reconnaissance, the ballistic wave was considered a noise signal. However, studies [16, 24-26] have shown that the ballistic wave is a valuable source of useful information, particularly information about the current level of barrel wear. In this research, a prospective method for verifying artillery shots based on the registration of the ballistic wave, formed by a projectile flying along a trajectory, by a spatially distributed system of acoustic sensors is proposed and investigated.

Goal and objectives of the research. The goal of the research is to develop and study a method for verifying artillery shots with random disturbances based on the registration of the ballistic wave, formed by a projectile flying along a trajectory, by a spatially distributed system of acoustic sensors.

To achieve the set goal, the following tasks were accomplished:

– Construction of the general scheme of the method;

– Development of a method for calculating the landing point of a projectile in a shot with random disturbances based on parabolic approximation;

– Conducting simulation modeling of the developed method;

– Comparison of the developed method with the method of compensating random disturbances using the artillery bracket method;

– Conducting a preliminary field experiment confirming the effectiveness of the developed method.

Main part

General Description of the Shot Verification Method

Figure 1 shows the layout of the gun and the measuring equipment.

The origin of the coordinates is aligned with the firing position of the gun P_0, shooting a projectile with an initial speed $\vec{v_0}$ exceeding the speed of sound *c*. The diagram shows the movement of the projectile in the vertical plane. The aiming point P_* is located at a horizontal range X_*. It should be noted that in this study, the lateral deviation of the projectile caused by drift is not considered. If necessary, this phenomenon can be accounted for quite simply using well-known methods [27,28]. During the flight of the projectile along a ballistic trajectory at supersonic speed, it is accompanied by a ballistic wave, observable on the surface along the line K of fire, lying inside the Mach cone. On the surface, at three observation points with corresponding coordinates $P_1(X_1), P_2(X_2), P_3(X_3)$, sets of measuring equipment (ME) are located. The ME is designed to register the moments of appearance of the ballistic wave at the respective point $\hat{t}_i, i = 1,2,3$, which correspond to the moment of the projectile's passage over the observation points. Each ME contains a measuring microphone (MM), an analog-to-digital converter, and a radio communication channel. Another set of ME is located at the firing position. All four sets of ME are synchronized in time.

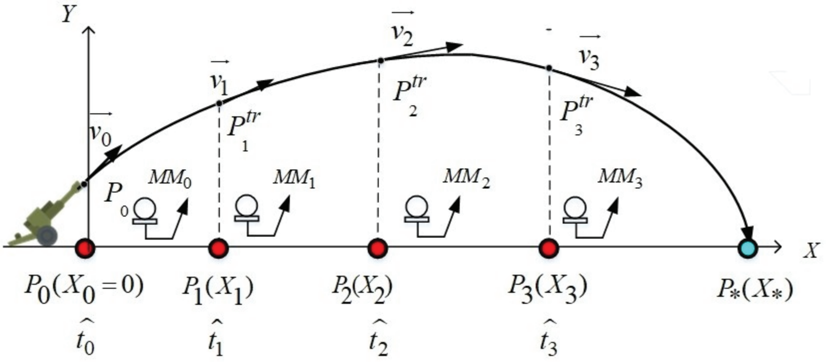

Figure 1. Layout of the Gun and Measuring Equipment

The task of the developed method for verifying a shot with random disturbances is to estimate the landing coordinate of the projectile based on the registered times of the projectile's flight over the observation points and to determine whether it satisfies the required accuracy.

Method of Measurement Processing

Step 1. For the firing point P_0, the projectile's speed is determined from the firing tables for the given type of projectile and charge (full firing preparation, random disturbances are possible). For each of the points $P_j\left(j=1,2,3\right)$, based on the data from the previous points $P_i\left(i=0,1,2\right)$, the following calculations are performed.

Step 2. The section of the projectile's trajectory $\overset{\frown}{P_i^{tr}P_j^{tr}}$ is approximated by a straight line segment $P_i^{tr}P_j^{tr}$ (Figure 2).

The air resistance force acting on the projectile in flight is described by a quadratic model [29]:

$$R = C_x \rho \frac{v^2}{2} SM, \tag{1}$$

where C_x – is the integral coefficient of resistance,

ρ is the air density,

v is the projectile speed,

S is the cross-sectional area of the projectile,

P_iP_j

$M = v/c$ is the Mach number,

c is the speed of sound in the air.

The vector $\vec{R}$ is directed opposite to the vector $\vec{v}$, therefore the force R gives the projectile a negative acceleration

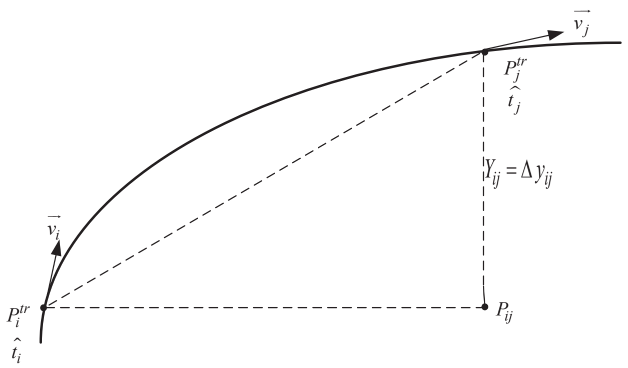

Figure 2. Calculated Section of the Trajectory

$$a = R / m, \tag{2}$$

where m is the mass of the projectile.

Then, the speed of the projectile at point P_j^{tr} is

$$v_j = v_j - C_x\rho\frac{v^2}{2}SM / m. \tag{3}$$

The approximate length of the trajectory segment

$$P_i^{tr}P_j^{tr} = v_i\Delta t_{ij} - C_x\rho\frac{v^2}{2}SM / m\Delta t_{ij}^2, \tag{4}$$

where $\Delta t_{ij} = t_j - t_i$.

As a result of performing computational procedures (1-4) in a right triangle, $P_i^{tr}P_j^{tr}P_{ij}$ two sides $P_i^{tr}P_j^{tr}$ and $P_i^{tr}P_{ij} = X_j - X_i$ are known. Then, the elevation of the projectile's flight trajectory along the Y-axis at point P_j^{tr} relative to point P_i^{tr} is:

$$\Delta Y_{ij} = \sqrt{(P_i^{tr}P_j^{tr})^2 - (P_i^{tr}P_{ij})^2}. \tag{5}$$

The height of the projectile's flight over point P_j is

$$Y_j = Y_j + \Delta Y_{ij} \tag{6}$$

As a result of the described computational procedure, points of the projectile's trajectory elevation over measurement points $P_1^{tr}\left(X_1, Y_1\right)$, $P_2^{tr}\left(X_2, Y_2\right)$, $P_3^{tr}\left(X_3, Y_3\right)$, and for the firing point $P_0\left(X_0 = 0, Y_0 = 0\right)$.

Step 3. Approximating parabolas are constructed for each triad of points:

$$\begin{gathered}(P_0,\ P_1^{tr},\ P_2^{tr}) - Y_1 = A_1X^2 + B_1X, \\ (P_0,\ P_2^{tr},\ P_3^{tr}) - Y_2 = A_2X^2 + B_2X, \\ (P_0,\ P_1^{tr},\ P_3^{tr}) - Y_3 = A_3X^2 + B_3X.\end{gathered} \tag{7}$$

Another approximating parabola can be constructed for four points:

$$(P_0,\ P_1^{tr},\ P_2^{tr},\ P_3^{tr}) - Y_4 = A_4X^2 + B_4X. \tag{8}$$

Each of these approximating parabolas serves as a model of the projectile's motion, to some extent compensating for the random disturbances in firing. The intersection points of the approximating parabolas with the surface (non-zero roots of the parabolas) $\mathrm{P}_*^1, \mathrm{P}_*^2, \mathrm{P}_*^3, \mathrm{P}_*^4$, are approximate estimates of the projectile's landing point. The arithmetic mean of the intersection points of the approximating parabolas with the surface $X_*^0 = \left(X_*^1 + X_*^2 + X_*^3 + X_*^4\right)/4$** is the averaged estimate of the projectile's landing point with compensated random disturbances.

It should be noted that in reality, more than four approximating parabolas are constructed, but in the end, exactly four are selected for the estimate X_*^0 according to the algorithm described below.

Algorithm for Sign Permutation ΔY_{ij}

In the calculation using relations (2-6), it was assumed that point j is located on the trajectory above point i. In a real situation, the Y-coordinate of point i may be greater than the Y-coordinate of point j. This can occur, in particular, if point j is located on the descending branch of the projectile's trajectory. Therefore, when estimating ΔY_{ij} using expression (5), both positive and negative values of ΔY_{ij} should be calculated. Accordingly, for each point $P_j, \left(j = 1,2,3\right)$, two values of the projectile's flight height over point P_j should be calculated:

$$Y_j^+ = Y_j + \Delta Y_{ij}, \qquad Y_j^- = Y_j + \Delta Y_{ij}. \tag{9}$$

Next, when constructing approximating parabolas for each point $P_j, (j=1,2,3)$, entering the triad (7) or tetrad (8), two parabolas are constructed – $Y_j^+ = A_j^+ X^2 + B_j^+ X$ and $Y_j^- = A_j^- X^2 + B_j^- X, (j=1,2,3)$. Then, for each of the two parabolas, the distance from the approximated landing point $\Delta_j^+ \left| X_{*j}^+ - X_* \right|, (j=1,2,3)$ and $\Delta_j^- \left| X_{*j}^- - X_* \right|, (j=1,2,3)$ are determined. The «correct» approximating parabola is chosen as the one with the smaller distance value $\Delta_j, (j=1,2,3)$.

The consideration of the mutual arrangement of points P_j and P_i, which is provided by the proposed algorithm, leads to the formation of four «correct» approximating parabolas in step 3 of the described method.

Simulation Modeling of the Shot Verification Method

The proposed method was modeled for firing from the FH70 howitzer with the M107 155 mm caliber projectile. Characteristics of the projectile [30]: weight 43 kg, diameter 0.15471 m, initial speed (full charge #8) 684.3 m/s. Firing preparation – complete. For calculations, ρ =1.2041 kg/m^3, c =341.6 m/s, aiming point coordinate X_*=25000 m. were adopted. The integral resistance coefficient C_x was chosen from tables [30]. X-coordinates of measurement points: $X(P_1)$=4900 м, $X(P_2)$=10000 м, $X(P_3)$ =16000 м. Flight times over measuring points, taking into account random disturbances $\hat{t}_i (i=1,2,3)$ were formed as follows: 5% random disturbances were introduced into the tabulated flight times:

$$\hat{t}_i = t_i^{FT} + \Delta t_i, \Delta t_i \in rand\left[0.95\Delta t_i; 1.05\Delta t_i\right](i=1,2,3).$$

Simulated parameters are presented in Table 1.

Using the described methodology, four approximating parabolas were constructed (see Figure 3).

The results of the simulation are presented in Table 2.

For clarity in the approximation process, Figure 4 shows the final sections of the approximating parabolas.

The simulation modeling of the proposed shot verification method demonstrates two main results:

1. The verification method, through the use of a system of approximating parabolas, compensates for random disturbances, achieving an error of about 0.5% of the firing range.
2. The proposed method allows for verification based on a single shot, obtaining verification results even before the projectile lands.

Comparative Analysis of the Proposed Method with Compensation of Random Disturbances by Consecutive Corrective Shots

To demonstrate the advantages of the proposed method, a model calculation of firing at the same range was carried out using a precise trajectory calculation program based on the NATO STANAG 4355 standard [31]. The projectile flight model underlying the standard describes the projectile as a moving material point with 5 degrees of freedom. It is currently considered the most accurate description of the projectile's trajectory for large calibers. Full modeling in accordance with [31] was conducted using Matlab software code, as detailed in [32]. To create equivalent modeling conditions, random disturbances in this case were introduced by pseudo-randomly changing the initial velocity of the projectile:

$$v_0^{dist} = v_0^{FT} + \Delta v_0, \Delta v_0 \in rand\left[0.975 v_0^{FT}; 1.025 v_0^{FT}\right]. \quad (9)$$

Table 1

Parameters of Simulation Modeling of the Shot Verification Method

Simulated Parameter	Parameters corresponding to the locations of microphones on the firing line		
	1	2	3
Aiming point coordinate, meters	25000		
Distance from the gun to the measuring microphone, meters	4900	10000	16000
Time of ballistic wave registration, seconds	10,5	22,2	39,7
Height of flight over the measurement point Y_j, meters	3634	6163	6686

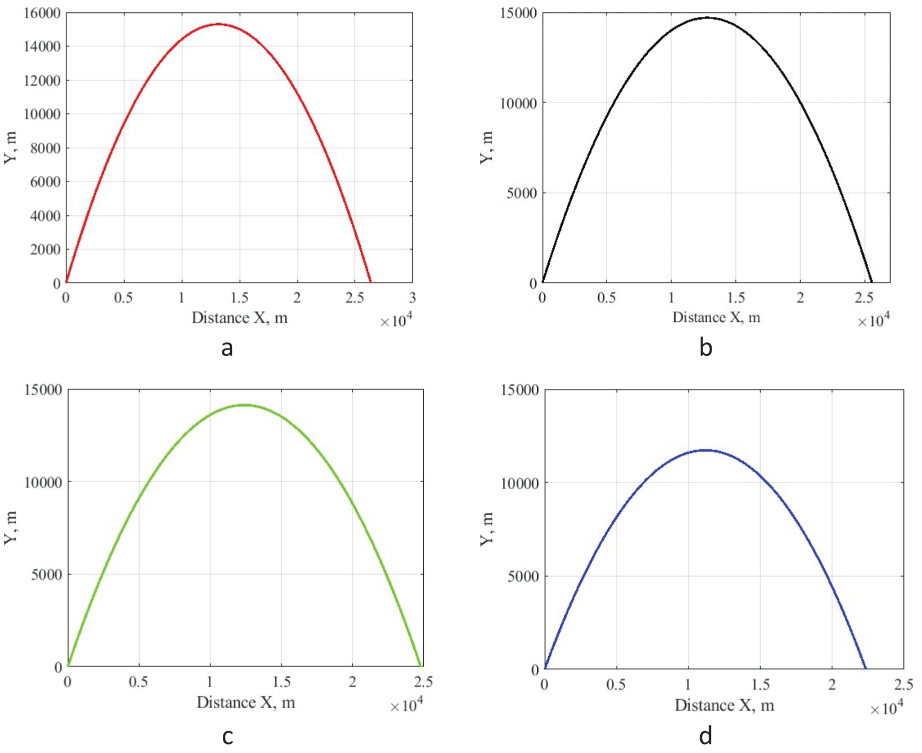

Figure 3. Approximating Parabolas (constructed: a – from points P_0, P_1, P_2, b – from points P_0, P_1, P_3, c – from points P_0, P_2, P_3, from points P_0, P_1, P_2, P_4).

Table 2

Results of the Simulation of the Shot Verification Method

Simulated Parameter		**Approximating Parabolas**			
		№1	**№2**	**№3**	**№4**
Aiming Range X_*, meters		25000			
Coefficients of the Equation for Each Parabola $Y = AX^2 + BX$	A	-0,000092	-0,000090	-0,000090	-0,000088
	B	2,28	2,30	2,11	2,32
X_*^i, meters		25070	25060	24610	22850
$\overline{X_*}$, meters		24390			

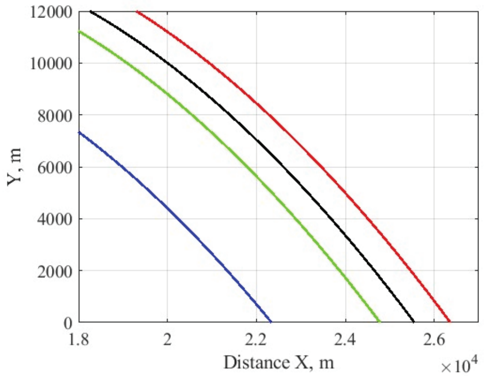

Figure 4. Final Sections of the Approximating Parabolas

After each shot, the deviation of the projectile's landing point was assessed, and its compensation was carried out using the artillery bracket method with aiming angle correction on subsequent shots. Figure 5 shows the projectile flight trajectories for five consecutive shots. The results of the simulation are presented in Table 3.

Figure 6 shows the final sections of ballistic trajectories for five consecutive shots.

The results of the simulation show that to compensate for random disturbances to an error level of 0.5% of the range, the traditional method of shooting adjustment requires at least five consecutive shots.

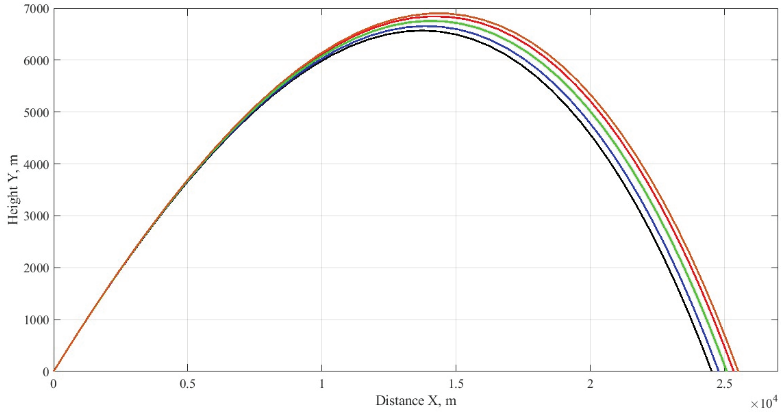

Figure 5. Calculated Ballistic Trajectories for Five Shots with Consecutive Correction

Table 3

Simulation Results of Compensating Random Disturbances with Consecutive Shots According to the STANAG 4355 Model

Simulation Results	**Shot Numbers**				
	№1	**№2**	**№3**	**№4**	**№5**
Aiming Range X_* , meters	15000				
$\overline{X_*}$, meters	24550	25530	24750	25300	25120
$\overline{X_*}$, meters	25120				

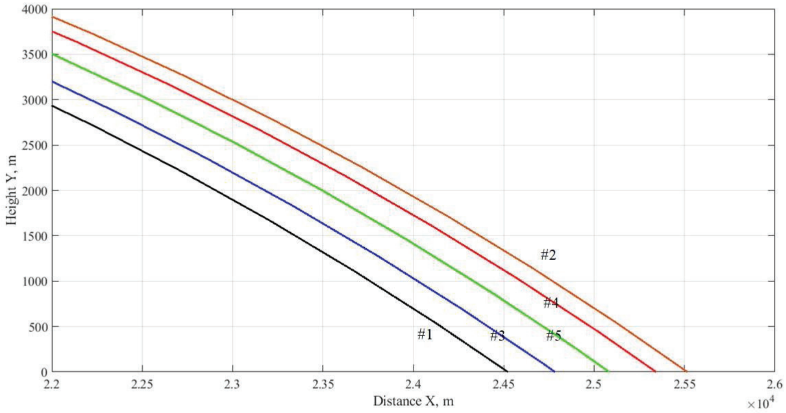

Figure 6. Final Sections of Ballistic Trajectories for Five Consecutive Shots

Experimental Confirmation of the Effectiveness of the Proposed Method

To confirm the effectiveness of the proposed shot verification method, a natural field experiment was conducted, registering real signals of the ballistic wave during training firing of the 152 mm towed gun 2A36 «Giatsint-B». Three sets of measuring equipment were placed at distances of 5400 m, 7800 m, and 10000 m from the firing position. Each set included a Rode NT-USB condenser microphone, a 16-bit TASCAM ADC, and radio communication channel-forming equipment with the firing position, where another measuring set was placed. All measuring equipment was synchronized. Due to the high level of acoustic noise and the low signal-to-noise ratio, the ballistic wave signal was recorded in a highly distorted form (see Figure 7). Determining the moment of arrival by the threshold method under such conditions was difficult, so the estimation of the times of arrival of the ballistic wave at the measuring microphones was carried out by determining the maximum of the cross-correlation function of the signals at the measurement point $s_i(t)$ and the signal at the firing position $s_0(t)$ [33]:

$$\hat{t}_i = \max R\left(s_i(t), s_0(t)\right), \left(i = 1,2,3\right). \qquad (10)$$

The appearance of the cross-correlation function is shown in Figure 8.

The results of the field experiment are presented in Table 4. It should be noted that in

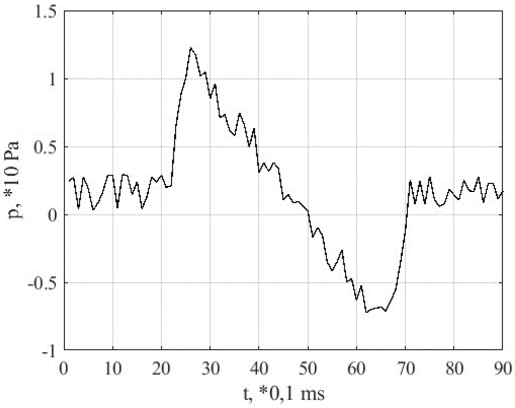

Figure 7. Signal of the Ballistic Wave Recorded at Measurement Point #1

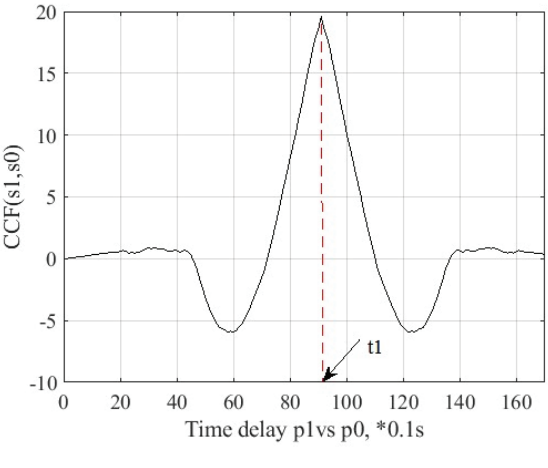

Figure 8. Appearance of the Cross-Correlation Function of the Signals at Point 1 and the Firing Position

Table 4

Parameters of the Experimental Verification of the Shot Verification Method

Parameter	**Parameters corresponding to the locations of microphones on the firing line**		
	1	**2**	**3**
Aiming point coordinate, meters	15000		
Distance from the gun to the measuring microphone, meters	5400	7800	10000
Time of ballistic wave registration, seconds	8,5	14,8	19,7
Height of flight over the measurement point Y_j, meters	3634	6163	6686

Table 5

Results of the Experimental Verification of the Shot Verification Method

Simulation Results		**Approximating Parabolas**		
		№1	**№2**	**№3**
Aiming Range X_*, meters		15000		
Coefficients of the Equation for Each Parabola $Y = AX^2 + BX$	A	-0,000096	-0,000088	-0,000080
	B	1,32	1,28	1,19
X_*^i, meters`		13790	14550	15100
$\overline{X_*}$, meters		14480		

this case, only three approximating parabolas were constructed, three points each.

During field trials, the proposed method provided compensation for random disturbances to a level of 3.5% of the range. This figure noticeably exceeds the result obtained in the simulation experiment. However, considering that it was obtained from a single shot, this result demonstrates an acceptable quality of verification.

Advantages and Disadvantages of the Proposed Shot Verification Method

The proposed verification method with parabolic approximation, as demonstrated by simulation modeling and a natural experiment, enables compensation for random disturbances to entirely acceptable error values of firing based on a single shot. The calculations related to the construction of approximating parabolas are relatively simple and can be performed on an artillery commander's tablet. The proposed method reduces the time of firing exposure of the weapon and decreases the expenditure of projectiles. In this regard, it opens new possibilities for preserving the combat capability of the weapon in counter-battery warfare. The main disadvantage of the proposed verification method is the need for specialized equipment to register sound fields and its placement along the line of fire. However, there is information about the development of such equipment and its pilot application [34,35].

Conclusions. A method for verifying artillery shots with random disturbances has been developed and studied. The method is based on registering the ballistic wave, formed by a projectile flying along a trajectory, by a spatially distributed system of acoustic sensors.

The developed method allows for the verification of a shot even before the projectile lands and bursts.

The computational simulation experiment demonstrated that the developed method significantly limits the time of firing exposure of the weapon and the expenditure of projectiles in compensating for random disturbances compared to traditional shooting adjustment. The natural field test confirmed the correctness of the main scientific and technical solutions underlying the studied verification method.

References:

1. Oprean, L.-G. (2020). Artillery from the perspective of firing effects and ensured capabilities. Scientific Bulletin Vol. XXV, No. 2(50) (pp. 107–113). DOI: 10.2478/bsaft-2020-0015.

2. John, Q.B. (2023). The More Things Change Russia's War in Ukraine Mirrors the Past as Much as It Shows the Future. Military Review, July, (pp. 1–14). Retrieved from: https://www.armyupress.army.mil/Journals/Military-Review/Online-Exclusive/2023-OLE/The-More-Things-Change/.

3. Shevtsov, R. (2023). An improved mathematical model of fire damage to enemy artillery units by missile forces and artillery in operations. Social Development and Security, 13(1), pp. 13–22. Retrieved from: https://doi.org/10.33445/sds.2023.13.1.2.

4. Shim, Y., & Atkinson, M.P. (2018). Analysis of artillery shoot-and-scoot tactics. Naval Research Logistics (NRL), 65(3), 242–274. Retrieved from: https://doi:10.1002/nav.21803.

5. Linfang, Q., Guangsong, C., Minghao, T., & Jinsong, T. (2022). General design principle of artillery for firing accuracy.Defence Technology, Vol. 18. Is. 12, pp. 2125–2140. Retrieved from: https://doi.org/10.1016/j.dt.2022.09.001.

6. Mady, M., Khalil, M., & Yehia, M. (2020). Modelling and production of artillery firing-tables: case-study. Journal of Physics: Conference Series, pp. 1507–1515. Retrieved from: https://doi.org/10.1088/1742-6596/1507/8/082043.

7. Mostafa, K. (2022). Study on modeling and production inaccuracies forartillery firing. Archive of mechanical engineering, Vol. 69. No. 1, pp. 165–183. Retrieved from: https://doi.org/10.24425/ame.2021.139802.

8. Petlyuk, I., & Shchavinsky, Y. (2021). Use of simulation modeling systems for determination of appropriate characteristics of prospective artillery weapons. Collection of scientific works of Odesa Military Academy, № 14, pp. 11–22. Retrieved from: https://doi.org/10.37129/2313-7509.2020.14.1.11-22.

9. Sun, Y., Zhang, S., Lu, G., Zhao, J., Tian, J. and Xue, J., (2022). Research on a Simulation Algorithm for Artillery Firepower Assignment According to Region. 3rd International Conference on Computer Science and Management Technology (ICCSMT), Shanghai, pp. 353–356. Retrieved from: https://doi.org/10.1109/ICCSMT58129.2022.00082.

10. Maneva, N.S., Achkoskib, J.Z., Petreskic, D.T., Gocićd, M.L., & Rančiće, D.D. (2017). Smart field artillery information system: model development with an emphasis on collisions in single sign-onauthentication. Military Technical Courier, Vol. 65. Issue 2, pp. 442–463. Retrieved from: https://doi.org/10.5937/vojtehg65-12703.

11. Sviderok, S.M., Shabatura, U.V., & Prokopenko, A.O. (2016). Technique of the fire correction of artillery systems according to modern requiremernts to the data preparation for shooting. Military Technical Collection, № 14, pp. 99–103. Retrieved from: https://doi.org/ 10.33577/2312-4458.14.2016.99-103.

12. Swietochowski, N. (2019). Rules of artillery employment in combat operations. Scientific Journal of the Military University of Land Forces, vol. 51, N. 2(192), pp. 280–293. Retrieved from: https://doi.org/10.5604/01.3001.0013.2599.

13. Krzyzanowski, S. (2018). How to assess the accuracy of artillery fire. Scientific Journal of the Military University Of Land Forces, vol. 50, no. 1 (187), p. 25–39. Retrieved from: https://doi.org/10.5604/01.3001.0011.7355.

14. Zasoby pidgotovky ta upravlinnya vognem artylerii: monografiia / Petrenko V.M., Lyapa M.M., Prykhodko A.I. Sumy:SumDU [in Ukrainian].

15. Šilinger, K., Brabcová, K., & Potužák, L. (2019) Assessment of Possibility to Conduct Fire for Effect without Adjust Fire according to Observational Distance of a Target in Artillery Automated Fire Control Systems. International Journal of Electrical Engineering and Computer Science.1: vol. 59, no. 1(197), p. 125–139.

16. Boltenkov, V., Brunetkin, O., Dobrynin, Y., Maksymova, O., Kuzmenko, V., Gultsov, P., Demydenko, V., & Soloviova, O. (2021). Devising a method for improving the efficiency of artillery shooting based on the Markov model. Eastern-European Journal of Enterprise Technologies, vol. 6. N. 3(114), pp. 6–17. Retrieved from: https://doi.org/10.15587/1729-4061.2021.245854.

17. Washburn, A.R. (2002). Notes on Firing Theory. Naval Postgraduate School Monterey, California, 37 p. Retrieved from: https://www.researchgate.net/publication/238621088_Notes_on_Firing_Theory.

18. Bartulović, V., Trzun, Z., & Hoić, M. (2023). Use of Unmanned Aerial Vehicles in Support of Artillery Operations. Strategos, N. 7(1), pp. 71–92. Retrieved from: https://www.researchgate.net/publication/372657457_Use_of_Unmanned_Aerial_Vehicles_in_Support_of_Artillery_Operations.

19. Oprean, L.-G. (2023). Artillery and drone action issues in the war in Ukraine. Scientific Bulletin vol. 28, No. 1(55), pp. 73–78. Retrieved from: https://doi.org/10.2478/bsaft-2023-0008.

20. Khudov, H., Yuzova, I., Lisohorskyi, B., Solomonenko, Y., Mykus, S., Irkha, A., Onishchuk, V., Sukonko, S., Semiv, G., & Bondarenko, S. (2021). Development of methods for determining the coordinates of firing positions

of roving mortars by a network of counter-battery radars. EUREKA: Physics and Engineering, N(3), pp. 140–150. Retrieved from: https://doi.org/10.21303/2461-4262.2021.001821.

21. Brzozowski, M., Pakowski, M., Nowakowski, M., Myszka, M. and Michalczewsk, M. (2019). Radars with the function of detecting and tracking artillery shells - selected methods of field testing. IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Turin, Italy, pp. 429–434. DOI: 10.1109/MetroAeroSpace.2019.8869656.

22. Kochan, R. et al. (2019). Theoretical Error of Bearing Method in Artillery Sound Ranging. 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Metz, France, 2019, pp. 615–619. DOI: 10.1109/IDAACS.2019.8924450.

23. Damarla, T. (2015) Battlefield Acoustics. Springer International Publishing Switzerland. 262 p. Retrieved from: https://doi.org/10.1007/978-3-319-16036-8.

24. Dobrynin, Y., Volkov, V., Maksymov, M., & Boltenkov, V. (2020). Development of physical models for the formation of acoustic waves at artillery shots and study of the possibility of separate registration of waves of various types. Eastern-European Journal of Enterprise Technologies, 4(5 (106), 6–15. Retrieved from: https://doi.org/10.15587/1729-4061.2020.209847.

25. Dobrynin, Y.V., Boltenkov, V.O., & Maksymov, M.V. Information technology for automated assessment of the artillery barrels wear based on SVM classifier. (2020). Applied Aspects of Information Technology.; vol. 3, No. 3, pp. 117–132. Retrieved from: https://doi.org/10.15276/aait.03.2020.1.

26. Dobrynin, E., Maksymov, M. & Boltenkov, V. (2020) Development of a method for determining the wear of artillery barrels by acoustic fields of shots. Eastern–European Journal of Enterprise Technologies. 2020; 3(5) (105): 6–18. Retrieved from: https://doi.org/10.15587/1729-4061.2020.209847.

27. Zhuravlyov, O.O., Orlov, S.V., & Shulyakov, S.O. (2020). Matematychna model traektorii polyotu snaryada dalekobiynoi artyileriyskoi systemy. Systemy ozbroennia I viiskovatehnika. 62–68. Retrieved from: https://doi.org/10.30748/soivt.2020.63.09.

28. Calculation. Military Operations Research, 27(3), 77–94. Retrieved from: https://www.jstor.org/stable/27166357.

29. Corvo, A. (2022). Comment on projectile motion with quadratic drag using an inverse velocity expansion. Am. J. Phys. 90, pp. 861–864. Retrieved from: https://doi.org/10.1119/5.0097411.

30. Wessam, M.E., & Chen, Z.H. (2015). Firing Precision Evaluation For Unguided Artillery Projectile. Proceedings of the 2015 International Conference on Artificial Intelligence and Industrial Engineering., Atlantis Press. pp. 584–587. Retrieved from: https://doi.org/10.2991/aiie-15.2015.156.

31. STANAG 4355 (2022). The Lieske modified point mass and five degrees of freedom trajectory models – AOP-4355 EDITION A. (No enabled versions). Washington DC, United States: United States Department of Defense,. Retrieved from: https://publishers.standardstech.com/content/military-dod-stanag-4355. Accessed: 2023-11-14.

32. Aldoegre, M. (2019). Comparison between trajectory models for firing table application. North-West University, Potchefstroom. Retrieved from: https://5dok.net/document/7q08x49y-comparison-between-trajectory-models-for-firing-table-application.html.

33. Le, O.B., Gervaise, C., & Mars, J.I. (2016). Time-Difference-of-Arrival Estimation Based on Cross Recurrence Plots, with Application to Underwater Acoustic Signals. Springer Proceedings in Physics, pp. 265–288. Retrieved from: https://hal.science/hal-01343668/document.

34. New Ukrainian art intelligence system «BARAK». Retrieved from: https://speka.media/v-ukrayini-testuyut-novu-sistemu-artrozvidki-barak-pozeyv.

35. «Hears» drones and missiles: how the FENEK system protects the infrastructure of Ukraine. Retrieved from: https://focus.ua/uk/digital/606501-slyshit-drony-i-rakety-kak-sistema-fenek-zashishaet-infrastrukturu-ukrainy-video.

Література:

1. OPREAN Laurean-Georgel. Artillery from the perspective of firing effects and ensured capabilities. Scientific Bulletin Vol. XXV, No. 2(50), 2020. P. 107–113. DOI: 10.2478/bsaft-2020-0015.

2. Bolton John Q. The More Things Change … Russia’s War in Ukraine Mirrors the Past as Much as It Shows the Future. Military Review, July 2023, p. 1–14. URL: https://www.armyupress.army.mil/Journals/Military-Review/Online-Exclusive/2023-OLE/The-More-Things-Change/.

3. Shevtsov R. An improved mathematical model of fire damage to enemy artillery units by missile forces and artillery in operations. Social Development and Security, 13(1), 2023. 13–22. https://doi.org/10.33445/sds.2023.13.1.2.

4. Shim Y., Atkinson M.P. (2018). Analysis of artillery shoot-and-scoot tactics. Naval Research Logistics (NRL), 65(3), 242–274. DOI:10.1002/nav.21803.

5. Linfang Qian, Guangsong Chen, Minghao Tong, Jinsong Tang, General design principle of artillery for firing accuracy/ Defence Technology, Volume 18, Issue 12, 2022, Pages 2125–2140, https://doi.org/10.1016/j.dt.2022.09.001.

6. Mady M., Khalil M., Yehia M. Modelling and production of artillery firing-tables: case-study. Journal of Physics: Conference Series, 1507(8), 082043. 2020. https://doi.org/10.1088/1742-6596/1507/8/082043.

7. Mostafa Khalil. Study on modeling and production inaccuracies for artillery firing. Archive of mechanical engineering. 2022. Vol. 69. No. 1, pp. 165–183. DOI: 10.24425/ame.2021.139802.

8. Petlyuk I., Shchavinsky Y. Use of simulation modeling systems for determination of appropriate characteristics of prospective artillery weapons. Collection of scientific works of Odesa Military Academy, 2021. № 14, p. 11–22. https://doi.org/10.37129/2313-7509.2020.14.1.11-22.

9. Sun Y., Zhang S., Lu G., Zhao J., Tian J. and Xue J. Research on a Simulation Algorithm for Artillery Firepower Assignment According to Region. 2022 3rd International Conference on Computer Science and Management Technology (ICCSMT), Shanghai, China, 2022, p. 353–356. DOI: 10.1109/ICCSMT58129.2022.00082.

10. Nikola S. Maneva, Jugoslav Z. Achkoskib, Drage T. Petreskic, Milan Lj. Gocićd, Dejan D. Rančiće. Smart field artillery information system: model development with an emphasis on collisions in single sign-on uthentication. Vojnotehnički Glasnik / Military Technical Courier, 2017. Vol. 65. Issue 2. P. 442–463. https://dx.doi.org/10.5937/vojtehg65-12703.

11. Sviderok S.M., Shabatura U.V., Prokopenko A.O. Technique of the fire correction of artillery systems according to modern requiremernts to the data preparation for shooting. Military Technical Collection, 2016. № 14, p. 99–103. https://doi.org/10.33577/2312-4458.14.2016.99-103.

12. Swietochowski N. Rules of artillery employment in combat operations. Scientific Journal of the Military University of Land Forces. 2019, Volume 51, Number 2(192), Pages 280–293. DOI: 10.5604/01.3001.0013.2599.

13. Krzyzanowski S. How to assess the accuracy of artillery fire. Scientific Journal of the Military University Of Land Forces, 2018. Vol. 50, no. 1(187). P. 25–39. http://dx.doi.org/10.5604/01.3001.0011.7355.

14. Засоби підготовки та управління вогнем артилерії / В.М. Петренко та ін. Суми : СумДУ, 2022. 458 с.

15. Šilinger Karel, Brabcová Kateřina, Potužák Ladislav. Assessment of Possibility to Conduct Fire for Effect without Adjust Fire according to Observational Distance of a Target in Artillery Automated Fire Control Systems. International Journal of Electrical Engineering and Computer Science. 2019; 1: 103–108.

16. Boltenkov V., Brunetkin O. , Dobrynin Y., Maksymova O., Kuzmenko V., Gultsov P., Demydenko V., Soloviova O. Devising a method for improving the efficiency of artillery shooting based on the Markov model. Eastern-European Journal of Enterprise Technologies, 2021, 6(3(114), 6–17. https://doi.org/10.15587/1729-4061.2021.245854.

17. Alan R. Washburn. Notes on Firing Theory. Naval Postgraduate School Monterey, California, 2002. 37 p. URL: https://www.researchgate.net/publication/238621088_Notes_on_Firing_Theory.

18. Valentina Bartulović, Zvonko Trzun, Matija Hoić. Use of Unmanned Aerial Vehicles in Support of Artillery Operations. Strategos, 2023, 7(1), 71–92. URL: https://www.researchgate.net/publication/372657457_Use_of_Unmanned_ Aerial_Vehicles_in_Support_of_Artillery_Operations.

19. Laurean-Georgel Oprean. Artillery and drone action issues in the war in Ukraine. Scientific Bulletin Vol. XXVIII, 2023, No. 1(55), 73–78. DOI: 10.2478/bsaft-2023-0008.

20. Khudov H., Yuzova I., Lisohorskyi B., Solomonenko Y., Mykus S., Irkha A., Onishchuk V., Sukonko S., Semiv G., Bondarenko S. Development of methods for determining the coordinates of firing positions of roving mortars by a network of counter-battery radars. EUREKA: Physics and Engineering, 2021, 3, 140–150. https://doi.org/10.21303/2461-4262.2021.001821.

21. Brzozowski M., Pakowski M., Nowakowski M., Myszka M. and Michalczewski M. Radars with the function of detecting and tracking artillery shells - selected methods of field testing, 2019 IEEE 5th International Workshop on Metrology for AeroSpace (MetroAeroSpace), Turin, Italy, 2019, pp. 429–434, DOI: 10.1109/MetroAeroSpace.2019.8869656.

22. Kochan R. et al. Theoretical Error of Bearing Method in Artillery Sound Ranging,» 2019 10th IEEE International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS), Metz, France, 2019, pp. 615–619. DOI: 10.1109/IDAACS.2019.8924450.

23. Thyagaraju Damarla. Battlefield Acoustics. Springer International Publishing Switzerland 2015, 262 p. https://doi.org/10.1007/978-3-319-16036-8.

24. Dobrynin Y., Volkov V., Maksymov M., Boltenkov V. Development of physical models for the formation of acoustic waves at artillery shots and study of the possibility of separate registration of waves of various types. Eastern-European Journal of Enterprise Technologies, 2020, 4(5 (106), 6–15. https://doi.org/10.15587/1729-4061.2020.209847.

25. Dobrynin Y.V., Boltenkov V.O., Maksymov M.V. Information technology for automated assessment of the artillery barrels wear based on SVM classifier. Applied Aspects of Information Technology. 2020. Vol. 3, No. 3: 117–132. https://doi.org/10.15276/aait.03.2020.1.

26. Dobrynin E., Maksymov M., Boltenkov V. Development of a method for determining the wear of artillery barrels by acoustic fields of shots. Eastern–European Journal of Enterprise Technologies. 2020, 3(5)(105): 6–18. DOI: https://doi.org/10.15587/1729-4061.2020.209847.

27. Журавльов О.О., Орлов С.В., Шуляков С.О. Математична модель траєкторії польоту снаряда далекобійної артилерійської системи. Системи озброєння і військова техніка. 2020. 62–68. 10.30748/soivt.2020.63.09.

28. Calculation. Military Operations Research, 27(3), 77–94. https://www.jstor.org/stable/27166357.

29. Antonio Corvo. Comment on projectile motion with quadratic drag using an inverse velocity expansion. Am. J. 2022. Phys. 90, 861–864. https://doi.org/10.1119/5.0097411.

30. Wessam M.E., Chen Z.H. Firing Precision Evaluation For Unguided Artillery Projectile. Proceedings of the 2015 International Conference on Artificial Intelligence and Industrial Engineering. 2015, Atlantis Press. 584–587. https://doi.org/10.2991/aiie-15.2015.156.

31. STANAG 4355 The Lieske modified point mass and five degrees of freedom trajectory models - AOP-4355 EDITION A. (No enabled versions). Washington DC, United States: United States Department of Defense, 2022. URL: https://publishers.standardstech.com/content/military-dod-stanag-4355. Accessed: 2023-11-14.

32. Aldoegre M. Comparison between trajectory models for firing table application. North-West University, Potchefstroom. 2019. URL: https://5dok.net/document/7q08x49y-comparison-between-trajectory-models-for-firing-table-application.html.

33. Olivier Le Bot, Cedric Gervaise, Jerome I. Mars. Time-Difference-of-Arrival Estimation Based on Cross Recurrence Plots, with Application to Underwater Acoustic Signals. Charles L. Webber, Jr.; Cornel Ioana; Norbert Marwan. Recurrence Plots and Their Quantifications: Expanding Horizons, 180, Springer, pp. 265–288, 2016, Springer Proceedings in Physics, 978-3-319-29921-1. ff10.1007/978-3- 319-29922-8_14ff. ffhal-01343668f https://hal.science/hal-01343668/document.

34. New Ukrainian art intelligence system «BARAK». URL: https://speka.media/v-ukrayini-testuyut-novu-sistemu-artrozvidki-barak-pozeyv.

35. «Hears» drones and missiles: how the FENEK system protects the infrastructure of Ukraine. URL: https://focus.ua/uk/digital/606501-slyshit-drony-i-rakety-kak-sistema-fenek-zashishaet-infrastrukturu-ukrainy-video.