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Yarovenko Vadim *Post graduate student*
Kharkiv National University of Radio Electronics
Nauky Ave. 14, Kharkiv, 61166, Ukraine
e-mail: vadym.yarovenko@nure.ua;
https://orcid.org/0009-0004-7116-2493

Improving the Accuracy of Target Coordinate Estimation in an Automated Acoustic System through Temporal Characteristics Analysis

The aim of the paper is developing an algorithm to enhance targeting accuracy by establishing a functional relationship between the bearing-angle error and the width of the time-decryption window, thereby improving the precision with which automated acoustic systems determine target coordinates

Relevance. Artillery acoustic reconnaissance (AAR) is a key component of counter-battery operations, as it enables covert, round-the-clock detection and high-precision localization of enemy firing positions by capturing and processing acoustic signals from gunfire and explosions. However, the practical effectiveness of conventional sound-ranging systems is significantly limited by the nonlinear influence of spatiotemporal gradients in meteorological fields (temperature and wind) and by errors in topogeodetic support. These factors cause considerable systematic and random shifts in the phase and time characteristics of signals, which in turn degrade the accuracy of spatial target localization.

Research methods. This paper develops a generalized mathematical model of the acoustic direction-finding process, in which the vertical-layered atmospheric profiles are described as piecewise-constant sub-models of a stratified medium, with rational approximations of temperature gradients and horizontal wind components. To enhance signal decoding robustness in environments with background noise, adaptive time windows with variable apodization are introduced, synchronized with the spectral evolution of the muzzle blast impulse. Based on this model, analytical expressions are derived for correcting phase and time shifts, which are integrated into a modified target localization algorithm for the standard AAR system AZK-7.

The results. Numerical experiments conducted for typical scenarios of unstable atmospheric stratification (inversion, isothermy, and super-adiabatic gradients) demonstrate a reduction in the root mean square error of coordinate estimation. The proposed approach does not require hardware upgrades and can be implemented within the software of existing sound-ranging systems of the Armed Forces of Ukraine by updating the data processing and ballistic computation modules. It is expected that this will increase the probability of neutralizing enemy batteries with the first counter-battery salvo by 10–15%, reduce the average response time of fire units by 30–40%, and lower ammunition expenditure in the forward zone.

Conclusion. A relationship between the temporal decoding window value and the error in determining the directional angle of the target, based on measurements from one of the base points, has been identified, and an algorithm for determining and accounting for this error magnitude has been developed. Prospects for further research include automated consideration of actual terrain relief using digital elevation models and the potential integration of unmanned aerial systems equipped with radio-acoustic sounding tools for real-time meteorological data updates.

Keywords: *acoustic reconnaissance, automated acoustic system, hardware-software complex, acoustic baseline, geometric baseline, acoustic ray, temporal decoding.*

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1 Introduction

The combat operations during the Russo-Ukrainian war have highlighted a critical need within the fire support units of the Rocket Forces and Artillery to enhance the accuracy of artillery reconnaissance systems. This improvement is essential for precisely locating enemy firing positions in order to conduct effective counter-battery operations and reduce the impact of hostile artillery on the units of the Armed Forces of Ukraine. One such reconnaissance tool is the automated acoustic (sound-ranging) system. However, due to outdated equipment, the influence of meteorological conditions, and limitations in topographic referencing accuracy, these systems currently provide insufficient precision in target coordinate determination. As a result, more ammunition is required to achieve effective counter-battery fire. An analysis of the tactical and technical characteristics of the AZK-7 system indicates that its target coordinate accuracy is insufficient for effective reconnaissance missions. When detecting a target at a distance of 10 km, the mean error in range is approximately 80 meters, and in direction — about 40 meters. This limitation is primarily due to one of the inherent disadvantages of acoustic reconnaissance: its strong dependence on meteorological conditions and terrain features. For instance, crosswinds can alter the direction of acoustic wave propagation, while the vertical distribution of meteorological elements can create either favourable or unfavorable conditions for reconnaissance. Under adverse conditions, the effective range of detection may decrease by a factor of 1.5 to 2. Additionally, accuracy is significantly affected by either the failure to account for or incorrect assessment of meteorological conditions and their variability along the acoustic propagation path. Moreover, the extended reconnaissance ranges impose stricter requirements on the accuracy of direction angle determination and the positioning of acoustic base lines. For example, a misalignment in the orientation of one of the 0–10 acoustic bases at a range of 15 km can result in a directional error of up to 150 meters and a range error of up to 300 meters. Such deviations may prevent target detection due to failure to meet the time decryption criteria.

Thus, enhancing the accuracy of target coordinate determination by automated acoustic systems through the analysis of time decryption data during target acquisition represents a current and significant research challenge.

2 Problem formulation and literature review

In recent years, the rapid advancement of computational technologies has enabled the widespread use of virtual computer experiments as a substitute for costly and sometimes hazardous full-scale physical tests. This shift has significantly reduced development time and expenses while enhancing design flexibility and safety. A number of efficient and highly accurate numerical methods have been developed, such as the finite element method (FEM), boundary element method (BEM), and computational fluid dynamics (CFD).These methods are now routinely employed in the analysis of complex structures in rocket engineering [1, 2] and power equipment design [3, 4]. These approaches allow engineers to simulate real-world conditions with remarkable precision, supporting optimization and failure prediction in highly demanding environments/

In the current context of full-scale aggression against Ukraine, mathematical modeling has become increasingly focused on improving the accuracy of enemy firing position localization.

A review of the literature and published materials concerning the improvement of sound-ranging system accuracy [5–10] indicates that this issue has received considerable attention, with various potential solutions being explored. However, the phenomenon of temporal signal decoding remains largely unaddressed. In existing works [7-8], it is used solely for associating bearings to targets with specific acoustic events, or for detecting errors in the “VO” mode (topogeodetic error detection mode). A detailed analysis of the temporal decoding phenomenon has revealed the possibility of developing an algorithm whose implementation in the target localization process would significantly enhance the overall accuracy and operational efficiency of the system. Decoding is the process of selecting the true location of a target from an array of calculated coordinates by comparing the time difference of signal arrival at the base points (BPs) with the difference in distances from the target to the BPs. This process involves analyzing the time difference of arrival (TDOA) measurements and matching them with theoretical values derived from geometric considerations. By minimizing the discrepancy between measured and expected time differences (typically using optimization or statistical estimation techniques such as least squares or maximum likelihood) the algorithm identifies the most probable position of the target, effectively filtering out spurious or ambiguous solutions.

3 The research aim and problem statement

The main aim of the paper is developing an algorithm to enhance targeting accuracy by establishing a functional relationship between the bearing-angle error and the width of the time-decryption window, thereby improving the precision with which automated acoustic systems determine target coordinates.

The task of performing time-based decoding arises due to the need to determine the coordinates of several targets that simultaneously reveal themselves through the sounds of gunfire. In complex acoustic environments, sound receivers register streams of acoustic signals that are partially organized during the initial processing.

As a result, a set of data related to various targets, including the time of arrival of the acoustic signals, is stored in the memory of the Central Processing Module (CPM) for each BP. If this time is not taken into account and the coordinates of the target are determined based only on the obtained directions (by solving a triangulation problem), nine intersection points will be obtained. The coordinates of six of these points (X1, X2, X3, X4, X5, X6) will be false.

For example, without time-based decoding, three directions from two base points result in nine intersection points, but only three of these can be true (see Fig. 3.1).

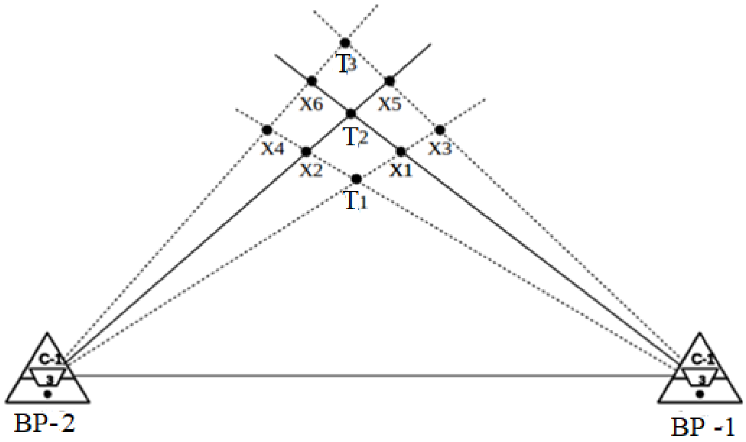


Figure 3.1. Target triangulation using two baseline points for simultaneous localization of multiple targets
Рисунок 3.1. Триангуляція цілі з використанням двох базових точок для одночасної локалізації множини цілей

Here BP-1, BP-2 are centers of the acoustic baselines used to determine the bearing to the target; T1, T2, T3 are true target coordinates; and X1, X2, X3, X4, X5, X6 are false target coordinates.

Thus, to perform temporal decoding, the signal arrival time is recorded with an accuracy of 2 ms, which allows for identification of the true target coordinates and elimination of false ones by computing the temporal decoding window.

4 Influence of topogeodetic referencing errors

Let us now consider the influence of topogeodetic referencing errors on the width of the temporal decoding window, i.e., the discrepancy between the actual and calculated time differences of signal reception at the baseline points.

To simplify the analysis, we choose a point such that the triangulation angle is close to 90° (see Fig. 4.1).

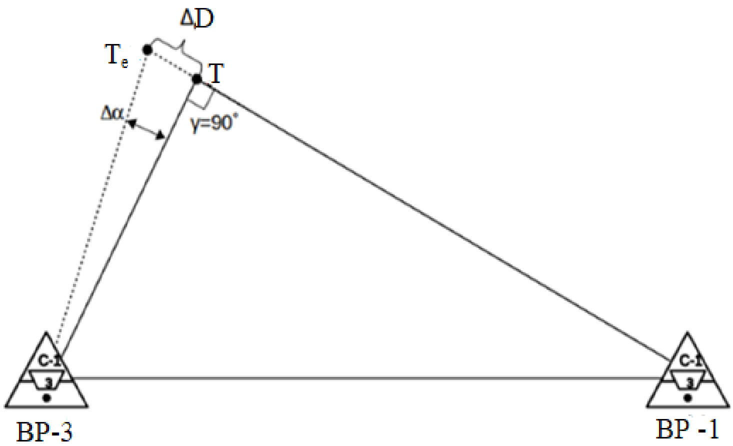


Figure 4.1. Influence of bearing angle error on target localization accuracy and the temporal decoding window

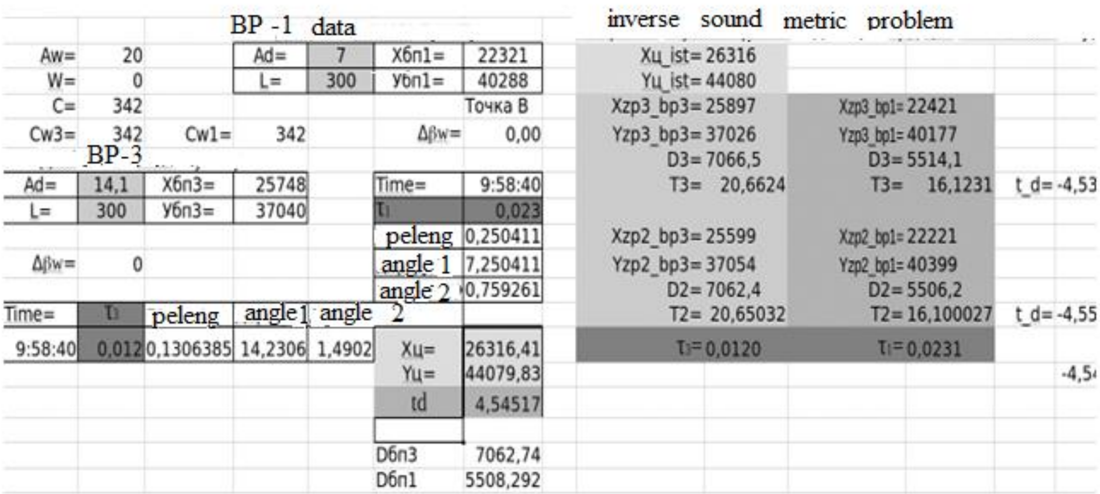
Рисунок 4.1. Вплив похибки кута пеленгування на точність локалізації цілі та часове вікно декодування

From Figure 4.1, it can be seen that the distance from the control point (CP) to base point BP-3 changes significantly less than the distance to base point BP-1, which changes by ΔD. Using the mil formula, the value of ΔD can be approximately calculated:

$$\Delta D = 0.001 D \Delta\alpha$$

Then the value of the temporal decoding window will change by ΔD / c (where c is the speed of sound in m/s). For example, for a target range of 4000 m and an orientation error of 0–10 mils, the difference in distances ΔD will be 40 m, and accordingly, the decoding window value for a sound speed of 340 m/s will be 0.1176 s. This value does not exceed the allowable limit of 0.8 s, but it can be detected by equipment operating with an accuracy of 0.002 s. Thus, based on the measured value of the temporal decoding window, it is possible to estimate the directional angle measurement error of the base point, assuming that all other top-geodetic reference data are accurate and that meteorological conditions remain uniform during the propagation of the acoustic wave.

To confirm this, we simulate the process of processing target interception results by secondary data processing equipment, in particular the determination of target coordinates and verification of the temporal decoding window. For this purpose, we use an Excel spreadsheet (Fig. 3) designed for manual processing of target interception results by base points. The directional angle error is assumed to be Δα = –0–10 mils. To perform this, it is necessary to use the Excel table? Presented in the Fig. 4.2 below



BP -1 data

Aw=	20		Ad=	7	Xбп1=	22321
W=	0		L=	300	Убп1=	40288
C=	342					Точка В
Cw3=	342	Cw1=	342		Δβw=	0,00
BP-3						
Ad=	14,1	Xбп3=	25748		Time=	9:58:40
L=	300	Убп3=	37040		τ_1	0,023
					peleng	0,250411
Δβw=	0				angle 1	7,250411
					angle 2	0,759261
Time=	τ_1	peleng	angle1	angle 2		
9:58:40	0,012	0,1306385	14,2306	1,4902	Xц=	26316,41
					Yц=	44079,83
					td	4,54517
					Dбп3	7062,74
					Dбп1	5508,292

inverse sound metric problem

Xц_ist= 26316		
Yц_ist= 44080		
Xzp3_bp3= 25897	Xzp3_bp1= 22421	
Yzp3_bp3= 37026	Yzp3_bp1= 40177	
D3= 7066,5	D3= 5514,1	
T3= 20,6624	T3= 16,1231	t_d= -4,53
Xzp2_bp3= 25599	Xzp2_bp1= 22221	
Yzp2_bp3= 37054	Yzp2_bp1= 40399	
D2= 7062,4	D2= 5506,2	
T2= 20,65032	T2= 16,100027	t_d= -4,55
τ_3= 0,0120	τ_1= 0,0231	
		-4,5

Fig. 4.2. Excel spreadsheet
Рис. 4.2. Електронна таблиця Excel

This Excel spreadsheet is used for directional angle error estimation.

5 Directional angle error estimations

The following algorithm is used for estimations of decoding window changes.

1. Using the inverse acoustic localization problem and the true coordinates, determine the time bearings τ for the first and third base points (τ_3 = 0.0120, τ_1 = 0.0231).
2. Insert the obtained τ values into the coordinate calculation algorithm and verify that the computed coordinates match the true ones.
3. Determine the time difference of acoustic signal arrival at BP-1 and BP-3 (td = 4.54517).
4. Introduce a bearing error (–0–10 mils) at the "bearing" input for base point BP-3 and record the change in the acoustic signal arrival time difference at BP-1 and BP-3 (td – 0.1).
5. Calculate the difference in temporal decoding windows, i.e., how the decoding window changes due to the directional angle error of the target, using Δtd = ((td – 0–10) – td). The calculation results are summarized in Table 1.

The results of calculation are presented in Table 5.1

Table 5.1 Results of temporal decoding window calculations
Таблиця 5.1 Результати розрахунків вікна тимчасового декодування

Target	Target Coordinates		Distances from Base Points to Target (m)		Time Differences (Temporal Bearing)		Signal Arrival Times at BP-1 and BP-3: Without Error (td) and With Error (td-0.1)		Temporal Decoding Window Δt_dec (td – td-0.1)
N	X	26402	D3	6955	τ_{bp3}	0,0001	td	4,275	0,083
	Y	43963	D1	5493	τ_{bp1}	0,0001	td-0,1	4,192	
1	X	25700	D3	4462	τ_{bp3}	0,0919	td	2,546	0,097
	Y	41500	D1	3592	τ_{bp1}	-0,332	td-0,1	2,449	
2	X	28000	D3	9239	τ_{bp3}	-0,133	td	3,461	0,077
	Y	46000	D1	8056	τ_{bp1}	0,0484	td-0,1	3,384	
3	X	25750	D3	8961	$\tau_{бп3}$	0,0823	td	6,717	0,076
	Y	46000	D1	6663	τ_{bp1}	0,2567	td-0,1	6,641	
4	X	23500	D3	7315	τ_{bp3}	0,3469	td	6,534	0,073
	Y	44000	D1	3896	τ_{bp1}	0,4434	td-0,1	6,461	
5	X	26400	D3	3034	τ_{bp3}	-0,107	td	-3,085	0,079
	Y	40000	D1	4090	τ_{bp1}	-0,631	td-0,1	-3,164	
6	X	24939	D3	3891	τ_{bp3}	0,2622	td	3,548	0,118
	Y	40844	D1	2677	τ_{bp1}	-0,438	td-0,1	3,430	
7	X	28000	D3	4991	τ_{bp3}	-0,319	td	-2,368	0,073
	Y	41500	D1	5800	τ_{bp1}	-0,438	td-0,1	-2,441	

The data in the table indicate that for all cases of temporal bearings (target positions both in front and in depth), a consistent value of the temporal decoding window is observed. This value depends on the directional error Δα and, to a lesser extent, on the distance to the target. Thus, the modeling results confirm the theoretical considerations regarding the change in the temporal decoding window in the presence of a target coordinate determination error. For example, the theoretically calculated error value for the case when the interception angle is close to 90° is 0.118 s, which closely matches the modeling result of 0.1176 s, confirming the reliability of the obtained results. In the case where the interception angle is not a right angle, as illustrated in Figure 2, the algorithm for determining the directional angle error will differ slightly. Let us consider this in more detail (Fig. 5.1).

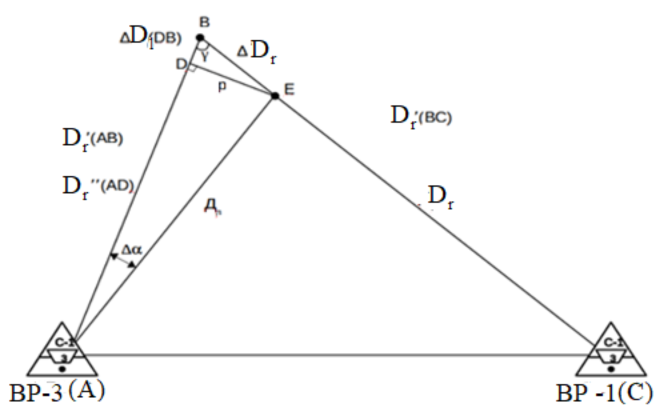


Fig. 5.1. Determination of the directional angle error from BP-3
Рис. 5.1. Визначення похибки кута напряму від BP-3

The presence of an angular error Δα changes the distances by ΔD_R and ΔD_L. To determine the magnitude of this change in distance, it is necessary to construct a segment p (segment ED in Figure 4), which forms a right triangle EBD. From the trigonometric relationships of the right triangle, the following formulas can be derived:

The presence of a directional angle error Δα results in changes to the distances, denoted as ΔD_p and ΔD_l. To determine the magnitude of these distance changes, it is necessary to construct segment p (segment ED in Figure 4), which forms a right triangle EBD. Based on the trigonometric relationships in the right triangle, the following formulas can be derived:

$$\Delta D_L = \frac{p}{\mathrm{tg}\gamma}, \qquad \Delta R_R = \frac{p}{\sin\gamma} \tag{5.1}$$

Thus, the difference in distances to the target will change by a value of ΔD

Based on the above, the following formulas can be derived:

$$\Delta D = \Delta D_R - \Delta D_L = \frac{p}{\sin\gamma} - \frac{p}{tg\gamma}.$$

Simplifying we have

$$\Delta D = p\left(\frac{1}{\sin\gamma} - \frac{\cos\gamma}{\sin\gamma}\right) = p\left(\frac{1-\cos\gamma}{\sin\gamma}\right).$$

Next, we determine the value of *p*:

$$p = \Delta D \div \left(\frac{1-\cos\gamma}{\sin\gamma}\right) = \Delta t_{dec} \cdot c \div \left(\frac{1-\cos\gamma}{\sin\gamma}\right). \tag{5.2}$$

It follows from Figure 5.1 that

$$D_L'' = D_{L(AB)}' - \Delta D_{L(DB)},\ D_L = \sqrt{\left(D_L''\right)^2 + p^2}. \tag{5.3}$$

Using the previously obtained values of *p* and D_l, the sine of the angle Δα is determined based on the definition of the sine as the ratio of the side opposite the angle (*p*, equation (5.2)) to the hypotenuse D_l, calculated using equation (5.3).

$$\sin\Delta\alpha = \frac{p}{D_L}. \tag{5.4}$$

Using the formulas provided above, an algorithm was developed and calculations were performed using the data for Target No. 7 from Table 4.1. The algorithm computes:

1. The value of segment *p* according to formula (5,2).

$$p = 0{,}073 \cdot 340 \div \left(\frac{1-\cos(8{,}53\cdot 6)}{\sin(8{,}53\cdot 6)}\right) \approx 51{,}82.$$

2. The change in distance for the left base point (ΔD_l) according to formula (1).

$$\Delta D_L = \frac{51{,}82}{\mathrm{tg}(8{,}53\cdot 6)} \approx 41{,}69.$$

3. The refined distance to the target for the left base point according to formula (5.3).

$$D_L'' = 5034 - 41{,}69 \approx 4992{,}3,\ D_L = \sqrt{(4992{,}3)^2 + (51{,}82)^2} \approx 4992{,}6.$$

4. The value of the directional angle error for the left base point according to the formula (5.4).

$$\sin\Delta\alpha = \frac{51{,}82}{4992{,}6} \approx 0{,}01037,\ \Delta\alpha = \frac{\arcsin(0{,}01037)}{6} \approx 0{,}099 \approx 0-10.$$

5. The refined directional angle to the target from the left base point.

$$\alpha_L = 10 - 44 + 0 - 10 = 10 - 54.$$

6. Refined target coordinates obtained by solving the forward geodetic problem for the left base point, using the values of ΔD_l and α_L calculated in the previous steps.

For Target No. 7, the initial coordinates with error were: X = 28059, Y = 41512. After performing the calculations according to the algorithm, the coordinates were refined to: X = 27996.

The initial coordinate Y was 41512, and after performing the calculations according to the algorithm, the refined coordinates were: X = 27996, Y = 41499. Thus, the presented algorithm confirms its effectiveness by refining the target coordinates by 63 m along the X-axis and 13 m along the Y-axis.

Conclusion

The results of the analysis of the dependence of the temporal decoding window on meteorological conditions indicate that under uniform meteorological conditions in the acoustic ray propagation area, this window will be independent of whether meteorological conditions are taken into account. It has been established that an error in determining the directional angle of the target, based on measurements from one of the base points, leads to a change in the temporal decoding window. A relationship between the temporal decoding window value and the error in determining the directional angle of the target, based on measurements from one of the base points, has been identified, and an algorithm for determining and accounting for this error magnitude has been developed. The effectiveness of the algorithm has been confirmed by calculations performed using data from an Excel worksheet. For Target No. 7 from Table 4/1, the coordinate determination errors were 63 m along the X-axis and 13 m along the Y-axis. To more accurately determine the coordinates of a target that emits sound from a shot, it is advisable to calculate the temporal decoding window and, based on it, determine the error in the directional angle measurement from a base point, especially when it is impossible to establish an acoustic reference point. In cases where directional angles from two base points are determined with errors, accounting for the cumulative error for one base point will not reduce the accuracy of coordinate determination by the acoustic system.

In the future, the created algorithm can be implemented in the software of the modernized AZK-7 hardware-software complex, enabling automation of calculations according to the algorithm and improving the accuracy of target coordinate determination by the system.

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Яровенко Вадим Аспірант
Харківський національний університет радіоелектроніки
Проспект Науки, 14, Харків, 61166,
e-mail: vadym.yarovenko@nure.ua;
https://orcid.org/0009-0004-7116-2493

Підвищення точності визначення координат цілі в автоматизованій акустичній системі шляхом аналізу часових характеристик сигналу

Мета дослідження - проведення аналізу процесу часового дешифрування, дослідження впливу похибок топогеодезичної прив'язки на визначення координат цілі та відображення їх на значенні часового дешифрування.

Актуальність. Артилерійська звукова розвідка (АЗР) – одна з ключових складових контрбатарейної боротьби, оскільки забезпечує приховане, цілодобове виявлення та високоточне визначення координат вогневих позицій противника шляхом реєстрації та оброблення акустичних сигналів пострілів і вибухів. Однак практична ефективність традиційних звукометричних комплексів істотно обмежується нелінійним впливом просторово-часових градієнтів метеорологічних полів (температури та вітру) і похибками топогеодезичного забезпечення, що призводить до значних систематичних та випадкових зсувів фазових і часових характеристик сигналу й, відповідно, до деградації точності просторової прив'язки цілей.

Методи дослідження. У статті розроблено узагальнену математичну модель процесу акустичного пеленгування, у якій висотно-шарові профілі атмосфери описуються як кусково-сталі субмоделі стратифікованого середовища із раціонально апроксимованими градієнтами температури та горизонтальними складовими швидкостей вітру. Для підвищення стійкості дешифрування у середовищі з фоновими завадами запропоновано адаптивні часові вікна зі змінною аподизацією, що синхронізуються зі спектральною еволюцією пострільного імпульсу. На основі цієї моделі отримано аналітичні співвідношення для корекції фазових та часових зсувів, які інтегровано у модифікований алгоритм обчислення координат цілі штатного комплексу АЗК-7.

Результати. Числові експерименти, проведені для сценаріїв типової нестійкої стратифікації (інверсія, ізотермія, супер-адіабатичні градієнти) продемонстрували зниження середньоквадратичної помилки визначення координат. Запропонований підхід не потребує апаратної модернізації та може бути впроваджений у системне програмне забезпечення наявних звукометричних комплексів Збройних Сил України через оновлення модулів оброблення даних та балюстичного центру. Очікується, що це забезпечить підвищення ймовірності ураження ворожих батарей першими ж контрзалпами на 10-15 %, скорочення середнього часу реакції вогневих підрозділів на 30-40 % та зменшення витрат боєприпасів у передовій зоні.

Висновки. Встановлено залежність між значенням вікна часового дешифрування та похибкою у визначенні дирекційного кута цілі за результатами засічки одним з базних пунктів, створено алгоритм визначення та врахування величини цієї похибки. Окреслено перспективи подальших досліджень, зокрема автоматизоване врахування реального рельєфу місцевості за цифровими моделями висот і можливість інтеграції з безпілотними засобами радіоакустичного зондування для оперативного оновлення метеоданих.

Ключові слова: *звукова розвідка, автоматизований звукометричний комплекс, програмно-апаратний комплекс, акустична база, геометрична база, акустичний промінь, часове дешифрування*

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