PHYSICAL SCIENCES

METHODOLOGY FOR DETERMINING THE LOCATION OF POTENTIALLY DANGEROUS OBJECTS IN THE ZONE OF REGIONAL ARMED CONFLICT

Dembitskyi V.
PhD student of NTUU "KPI named after I. Sikorsky", Kyiv
Kratko O.
Junior Researcher of the Special Design Bureau "Storm", NTUU "KPI named after I. Sikorsky", Kyiv
https://doi.org/10.5281/zenodo.13619749

Abstract
The article discusses the provisions of the methodology for determining the location of potentially dangerous objects in the zone of regional armed conflict.

Keywords: location determination, potentially dangerous object.

Statement of the problem in general. The results of the analysis of research in the field of seismic location [1] made it possible to conclude that it is expedient to use signaling devices (SZ) to solve the problems of environmental monitoring, the solution of which will ensure the implementation of the functions of automatic detection and location (VMP) of potentially dangerous objects (PNO) in the zone of regional armed conflict with the possible occurrence of an emergency at the facility:

determination of PNO coordinates taking into account the sphericity of the seismic wave propagation front, which reduces the systematic error of the VMP;

reduction of the ambiguity of the VMP that arises when solving the system of nonlinear equations by which the coordinates are determined.

The purpose of the publication is that the result of solving these problems is the developed model of VMP [2], which is based on the functioning of the Seibel direction finder. The model is designed to determine the coordinates of an object by a triad of seismic sensors while removing the restriction on the topology of the triad of reception points. At the same time, the VMP has the following features:

only passive means are used;

there is no accurate a priori information about the parameters of the signal from the object and its coordinates;

the need to determine the coordinates at all points of the sensitive area of the locator;

invariance of the topology of reception points on the ground.

However, the question of unambiguous solution of the coordinometric problem for the VMP PNO has not been found, which determined the purpose of the work.

Analysis of the latest research and publications, in which the solution of this problem was initiated and on which the author relies. The fourth task needs to be solved. Let us give a brief description of the VMP model in accordance with the publication [1]. The task of determining the coordinates of the PNP in the zone of regional armed conflict, as an object of location, on the plane according to a set of measured values of range differences with respect to several pairs of passive non-directional receivers, which are located at fixed points, is reduced to a mathematical formulation. There is a set of fixed points *A, B, C,* given by their coordinates $\langle x_A, y_A \rangle$, $\langle x_B, y_B \rangle$, $\langle y_C, y_C \rangle$ respectively in some system Coordinate. With respect to the point *D*, the coordinates of which are to be determined, it is known that the difference in the distances from it to pairs of points *I* and *J* is equal to $\Delta r_{IJ} \equiv |ID| - |JD|$ ($I, J \in \{A, B, C\}$). The described general algorithm for determining coordinates involves the calculation of the roots of a system of nonlinear equations that relate the initial data to the coordinates of a point *D* [2].

In the *xOy* coordinate system, the hyperbola lines are given by a system of three equations that describes the position of the location object when using three receivers with an arbitrary topology. The solution to the system of equations is several roots, among which are the coordinates of the point of location of the object on the plane. So, to determine the coordinates, it is necessary to use three passive receivers, which will allow you to control two parameters of the object, namely: range differences between the location of the object and the reception points. The parameters define the hyperbola lines and the bearing line, which are the lines of the object's position. A prerequisite for determining the coordinates is to obtain the coordinates of the point of intersection of one of the hyperbola lines and the bearing line

$$y = y_0 + x tg\gamma ,$$

where y_0 - is the ordinate of the crossing of the bearing line of the *Oy* axis ;

g is the bearing angle of the PNO, the definition of which is given in [2].

The line of position of the source of a powerful seismic signal due to an explosion, such as a munition, as the PNO of the location, crosses the *Ox* axis at an angle *g* and passes through the observation point $F(x_F, y_F)$, which has variable coordinates relative to the center of the coordinate system. It is necessary to find the coordinates of the point that is the intersection of the lines of the hyperbola and the line.

When simultaneously transferring the origin of the coordinate system to a point $Y_0(0, y_0)$ and rotating the coordinate axes by an angle γ (Fig. 1), the coordinate transformation equation have the form of

$$\begin{cases} x = x'\cos\gamma - y'\sin\gamma; \\ y = y_0 + x'\sin\gamma - y'\cos\gamma, \end{cases}$$

where are x', y' the coordinates of the PNO (point D) in the coordinate system.

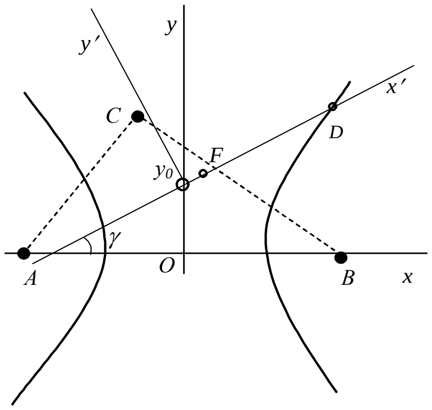

Figure 1 – Determination of PNO coordinates at point D: , , – points of reception of signals by seismic sensors

Since, as a result of the transformation of the coordinate system, the line of the line (bearing) is collinear of the axis $O'x'$, the system of equations, taking into account the considered system of equations, is given in the $x'O'y'$ coordinate system, equating the value of the variable zero [1]

$$\begin{cases} a_1(x'\cos\gamma)^2 + \mathrm{b}_1(y_0 + x'\sin\gamma)^2 + f_1 = 0; \\ a_2(x'\cos\gamma)^2 + b_2(y_0 + x'\sin\gamma)^2 + c_2(x'\cos\gamma)(y_0 + x'\sin\gamma) + \\ \qquad + d_2(x'\cos\gamma) + e_2(y_0 + x'\sin\gamma) + f_2 = 0; \\ a_3(x'\cos\gamma)^2 + b_3(y_0 + x'\sin\gamma)^2 + c_3(x'\cos\gamma)(y_0 + x'\sin\gamma) + \\ \qquad + d_3(x'\cos\gamma) + e_3(y_0 + x'\sin\gamma) + f_3 = 0. \end{cases}$$

It should be noted that functionally the equations of the system are interconnected through certain parameters γ, y_0 and range differences. Therefore, in the future, it is possible to apply only one equation. As a result of the transformation of the first equation of this system,

$$x'^2(a_1\cos^2\gamma - \sin^2\gamma) - x'2\mathrm{y}_0\sin\ \gamma - y_0^2 + f_1 = 0.$$

Coordinates are determined in the $x'O'y'$ coordinate system. Determine the coordinates of the point of intersection of the lines of the position of the PNO when taking into account $x' = L$. Then, equations are obtained that describe the coordinates of the object's location (Tables 1, 2) [1].

Table 1

Model of two-digit determination of the coordinates of an object

Parameter	Mathematical expression of a parameter	Number Formula
Distance from the observation point (the point of intersection of the ordinate axis with the bearing $Y_0(0, y_0)$) to the PNO	$L_1 = \dfrac{y_0\sin\gamma + \sqrt{y_0^2\sin^2\gamma - (a_1\cos^2\gamma - \sin^2\gamma)(f_1 - y_0^2)}}{(a_1\cos^2\gamma - \sin^2\gamma)}$ $L_2 = \dfrac{y_0\sin\gamma - \sqrt{y_0^2\sin^2\gamma - (a_1\cos^2\gamma - \sin^2\gamma)(f_1 - y_0^2)}}{(a_1\cos^2\gamma - \sin^2\gamma)}$	(1)
PNO bearing cut (Saibel pseudobearing)	$\gamma = arctg((2a\Delta r_{AC} - (a + x_3)\Delta r_{AB})/(y_3\Delta r_{AB}))$	(2)

Ordinate of intersection of the bearing line of the ordinate axis	$y_0 = y_F - x_F tg\gamma = \frac{y_3^2 + r_{AC} r_{AB} - r_{AC}^2 - a^2}{2y_3}$	(3)

Table 2

Notations that are accepted in Table. 1

Accepted designations	Description of the designation
$\begin{cases} x_F = -(2a\Delta r_{AC} - (a + x_3)\Delta r_{AB})(a^2 + \Delta r_{AC}^2 - \Delta r_{AC}\Delta r_{AB} - d^2)\Delta r_{AB} / 2Z; \\ y_F = -y_3(4a^2 - \Delta r_{AB}^2)(a^2 - d^2 + \Delta r_{AC}(\Delta r_{AC} - \Delta r_{AB}))/ 2Z. \end{cases}$ where $d = \sqrt{x_3^2 + y_3^2}$; $Z = 4a^2(y_3^2 + \Delta r_{AB}\Delta r_{AC} - \Delta r_{AC}^2) - \Delta r_{AB}^2(a^2 + d^2) + 2ax_3(2\Delta r_{AC}\Delta r_{AB} - \Delta r_{AB}^2)$	Coordinates of Observation Point *F*
$\Delta r_{AB} - \Delta r_{AC} = -\Delta r_{BC}$, where $\Delta r_{AB} = t_{AB}V_c$; $\Delta r_{AC} = t_{AC}V_c$; $\Delta r_{BC} = t_{BC}V_c$	Parameters that are controlled when determining coordinates
$a_1 = (2a / \Delta r_{AB})^2 - 1$; $b_1 = -1$; $f_1 = (\Delta r_{AB} / 2)^2 - a^2$	Variables Defined by Hyperbola Parameters
$A(-a,0)$, $B(a,0)$, $C(x_3, y_3)$; $a = \frac{\|AB\|}{2}$, $b = \frac{\|AC\|}{2}$, $c = \frac{\|BC\|}{2}$	Topology points and bases of reception points

Note: t_{AB}, t_{AC}, t_{BC} – the delay time of wave propagation between the reception points, which are located at the points A, B, C; V_c - is the average value of the seismic wave propagation velocity.

In comparison with the method of successive approximations in determining the coordinates of an object, the considered model allows to obtain an accurate analytical solution of the system of hyperbolic equations for determining the coordinates of an object by a triad of reception points in the absence of iterative procedures that make it impossible to process a significant flow of data on a real-time scale. Compared to the method of accurate analytical determination of the bearing of the object, the model allows you to determine the distance to the object in addition to the bearing. Compared to the methods of accurate analytical calculation of the coordinates of the object, in this model the restrictions on the type of topology of reception points are removed, and the bearing of the object is applied, which uniquely determines its location.

Presentation of the main material. It is expedient to use the considered model of VMP, which works for any sensor topology. To implement the function of the VMP in the environmental monitoring system, it is necessary to install the SZ of border protection on the demarcation line not in one line, but in two lines, Fig. 2.

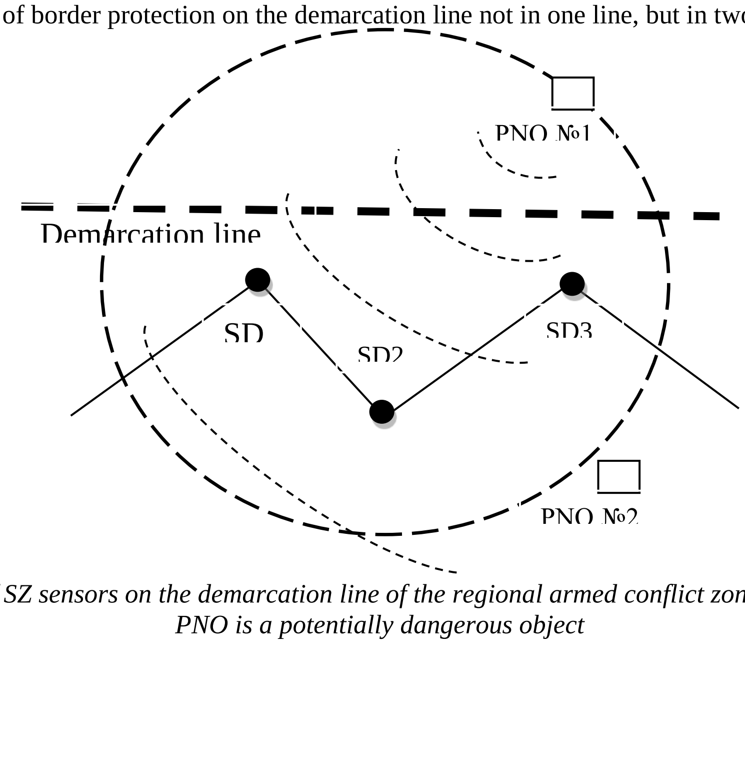

Figure 2 – Layout of SZ sensors on the demarcation line of the regional armed conflict zone: SD – alarm sensor; PNO is a potentially dangerous object

The topology of the sensors can be arbitrary, the average distance between them is determined by the task of protecting the border and is about 50 m. At the same time, the range of detection of PNO on our or adjacent side is tens of kilometers.

The use of the model (Table 1) makes it possible to find the points of intersection of the bearing and hyperbola lines, which distinguishes the model from the existing ones, where the location is considered as the intersection of two hyperbolic lines. At the same time, the maximum number of points of the probable location of the object has been reduced to two, which is two times less compared to the current methods of determining coordinates. This reduces the amount of subsequent rejection of coordinates. The solution of equation (1) Table. 1 can be 1 or 2 distance values, of which one is true.

The distance from the observation point (the point of intersection of the ordinate axis by the bearing $Y_0(0, y_0)$) to the PNO is determined by one of the expressions (1) of Table. 1 (L_1, L_2). At the same time, depending on the topology of the triad of reception points and bearing on the object, one value of the distance will be true. So, for example, for a rectangular isosceles topology, provided that the distance from the observation point to the object significantly exceeds the base of the triad $L_1, L_2 > a$, the bearing angle $\pm 45^0$ is approximately the boundary of the transition for determining the distance from the indicator L_1 to L_2 at positive bearing values. Also, it should be noted that the values of L_1 or L_2 can be with a minus sign, indicating the location of the object in the II or III coordinate angle.

Therefore, the considered mathematical model has been improved, and the parameter of signal strength has also been considered. Since the physical nature of the power parameters and the range difference are different, it is therefore possible to make an equation for estimating, for example, the parameter of the radius of the circle of the line of position of the object L_p, while the equation will include measuring the time and power of the signal, Fig. 3.

$$L_{д}^2 = (X_j - X_c)^2 + Y_c^2 \qquad (1)$$

where X_j, L_p is the abscissa of the center and the radius of the circle, as the lines of position of the PNO, determined by the parameter of the signal power at two reception points [2]:

$$X_j = \frac{a(P_a + P_b)}{P_a - P_b}, \; L_p = \frac{2a\sqrt{P_a P_b}}{P_a - P_b}, \qquad (4.5)$$

where P_a, P_b is the power of the received signal by two separated reception points $A(-a,0)$, $B(a,0)$.

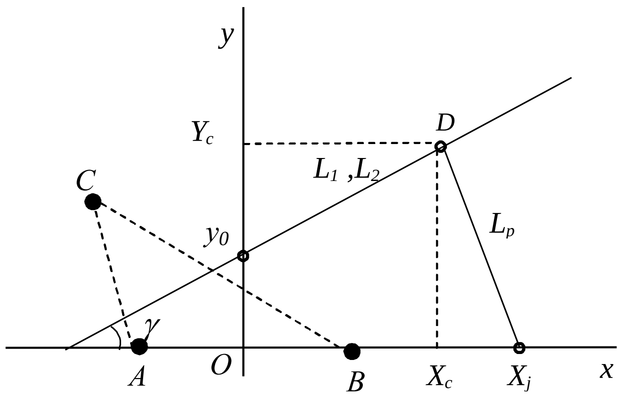

Figure 3 – Unambiguous determination of PNO coordinates at point D

To reduce the ambiguity of the solution, an additional measurement of the signal strength parameter at two separated reception points was considered. The coordinates of the PNO are related to the distance L_1 or L_2, obtained from the formulas (1) of Table. 1, expressions

$$X_c = L_1(L_2)\cos\gamma, \; Y_c = y_0 + L_1(L_2)\sin\gamma$$

The true value of the distance L_1 or L_2, at which the difference between the determination of the indicator L_p by power parameters and the difference in ranges will be minimal

$$N_1 = \left| L_p^2 - (X_j - L_1 \cos(\gamma))^2 - (L_1 \sin(\gamma) + y_0)^2 \right|, \tag{2}$$

$$N_2 = \left| L_p^2 - (X_j - L_2 \cos(\gamma))^2 - (L_2 \sin(\gamma) + y_0)^2 \right|, \tag{3}$$

where N_1, N_2 are the modulus of the difference of the squares of the radii of the circles, as the lines of the position of the PNO, determined by the parameters of time and power.

The criterion for the unambiguous determination of coordinates is the solution of the system of inequalities

$$L = \begin{cases} L_1 \ , \ \ N_1 < N_2 \\ L_2 \ , \ \ N_2 < N_1 \end{cases}, \tag{4}$$

According to criterion (4), choose one of the distances for which the square of the difference in distances will be the smallest, such a distance will be true, and the solution will be unambiguous.

The essence of the model for reducing the ambiguity of the determination of the PNO coordinates by a three-position passive seismic means is to determine the bearing of the PNO by the triad of reception points of an arbitrary topology and differs in that the sought coordinates are determined as the coordinates of the point of intersection of the hyperbola and bearing lines, which are the lines of position of the PNO, while ensuring the invariance of calculations to the topology of reception points and reducing the ambiguity of determining the coordinates. This reduces the probability of gross mistakes due to the ambiguity of the solution of the coordinometric problem. In this case, the control parameters are the delay time of wave propagation between the receiving points and the signal strength at the two reception points.

Taking into account the above, the methodology for determining the location of potentially dangerous objects in the zone of regional armed conflict is implemented according to the following algorithm:

1. Place three seismic sensors at spaced points $A(-a,0)$, $B(a,0)$, $C(x_C, y_C)$ of arbitrary topology.

2. Receive signals to all three non-directional sensors at times $t_A;\ t_C;\ t_B$.

3. Two independent differences in the time $t_{AB};\ t_{AC}$ of signal reception are measured by pairs of sensors that form measuring bases $a = \frac{|AB|}{2}$, $b = \frac{|AC|}{2}$, $c = \frac{|BC|}{2}$.

4. Calculate exactly the angle of the Seibel bearing according to the formula (2) Table. 1 $\gamma = arctg\left(\left(2at_{AC} - (a + x_3)t_{AB}\right)/\left(y_3 t_{AB}\right)\right)$.

5. Make equation (1) table. 1 to calculate the distance to the PNO by the parameter of the difference in the time of signal reception and determine it

$$L_1(L_2) = \frac{y_0 \sin\gamma \pm \sqrt{y_0^2 \sin^2\gamma - (a_1 \cos^2\gamma - \sin^2\gamma)(f_1 - y_0^2)}}{(a_1 \cos^2\gamma - \sin^2\gamma)}.$$

7. If the decision under clause 5 is ambiguous, then according to the criterion $L = \begin{cases} L_1 \ , \ \ N_1 < N_2 \\ L_2 \ , \ \ N_2 < N_1 \end{cases}$, according to the parameter of signal strength, one of the two distances is selected, the latter is taken as the true unambiguous VPM PNO.

8. At certain coordinates, a target designation is issued for deployment along with optical, thermal imaging surveillance equipment, or a UAV flight is carried out in order to detect signs of an emergency.

The determination of coordinates is carried out on the basis of the functioning of the Seibel direction finder with the addition of processing of signal strength values at reception points.

Conclusion. Thus, the methodology for determining the location of potentially dangerous objects in the zone of regional armed conflict has been improved, which is distinguished by obtaining analytical dependencies for the unambiguous determination of PNO coordinates due to the complex processing of time and amplitude parameters of the signal of a three-position seismic monitoring instrument. The use of the model made it possible to increase the efficiency of automatic detection of PNW in the zone of regional armed conflict under the influence of VTN due to ensuring the invariance of the topology of the three seismic signal reception points and reducing gross monitoring errors due to the ambiguity of the coordinates.

The validity and reliability of scientific results, conclusions and recommendations is ensured by the correct use of the tested mathematical apparatus, the completeness of taking into account reliable initial data and the definition and observance of appropriate restrictions and assumptions, the convergence of theoretical provisions with the results of modeling when using the current software, as well as when applying the current principles for verifying the reliability of the results.

Prospects for further research in this direction. The considered technique does not provide reliable data with significant fluctuations in the speed of the seismic wave in the direction of different sensors. Therefore, it is promising to develop a method for compensating for the error of calculations due to the variation of this speed.

References:

1. Seismoclatsion fiber-optic telecontrol of distributed security areas: monograph / I. S. Katerynchuk, M. I. Lysyi., V. G. Solonnikov − Khmelnytskyi: Publishing House of the National Academy of the State Border Guard Service of Ukraine named after B. Khmelnytsky, 2013. − 162 p.

2. Stalemate. RU 2258242 C2, IPC G01S 3/46, 11/02. Difference-Rangefinder Method of Direction Finding of a Radio Emission Source and Its Implementing Device / Saibel A. G., Patent Holder of the Military Institute. -cosm. acad. – № 2003118800/09; declared. 23.06.2003; publ. 10.08.2005

3. Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2018.08.034. References Aleqabi, G.I., Wysession, M.E., Ghalib, H.A.A., 2015. Characterization of seismic sources from military operations in Urban Terrain (MOUT): examples from Baghdad. Bull. Seismol. Soc. Am. 106, 23–41.

4. Arrowsmith, S., Whitaker, R., Le Pichon, A., Cansi, Y., Brachet, N., Charbit, M., Park, J., Stump, B., Che, I.-Y., 2012. Development and validation of infrasound data processing algorithms. In: Proceeding of the 2012 Monitoring Research Review: Ground-Based Nuclear Explosion Monitoring Technologies 2, pp. 665–675.

5. Beyreuther, M., Barsch, R., Krischer, L., Megies, T., Behr, Y., Wassermann, J., 2010. ObsPy: a Python toolbox for seismology. Seismol. Res. Lett. 81 (3), 530. Blom, P., 2013. Interaction of the Cyclonic Winds with the Infrasonic Signal Generated by a Large Maritime Storm. Dissertation, University of Mississippi. ProQuest/UMI (UMI No. 3567512).

6. Blom, P., Waxler, R., 2012. Impulse propagation in the nocturnal boundary layer: analysis of the geometric component. J. Acoust. Soc. Am. 131 (5), 3680–3690.

7. Ceranna, L., Le Pichon, A., Green, D.N., Mialle, P., 2009. The Buncefield explosion: a benchmark for infrasound analysis across Central Europe. Geophys. J. Int. 177, 491–508.

8. Chunchuzov, I., Kulichkov, S., Popov, O., Hedlin, M., 2014. Modeling propagation of infrasound signals observed by a dense seismic network. J. Acoust. Soc. Am. 135 (1), 38–48.

9. Chung, J.-K., Yeh, Y.T., 1997. Shallow crustal structure from short-period Rayleighwave dispersion data in southwestern Taiwan. Bull. Seismol. Soc. Am. 87 (2), 370–382.

10. ESI SAS (Earth Science Institute of The Slovak Academy of Sciences), 2004. National Network of Seismic Stations of Slovakia. Deutsches GeoForschungsZentrum GFZ.

11. Evers, L.G., Ceranna, L., Haak, H.W., le Pichon, A., Whitaker, R.W., 2007. A seismoacoustic analysis of the gas-pipeline explosion near Ghislenghien in Belgium. Bull. Seismol. Soc. Am. 97, 417–425.

12. Fuchs, F., Kolínský, P., Gröschl, G., Bokelmann, G., The AlpArray Working Group, 2016. AlpArray in Austria and Slovakia: technical realization, site description and noise characterization. Adv. Geosci. 43, 1–13.

13. Gráczer, Z., Szanyi, G., Bondár, I., Czanik, C., Czifra, T., Gyori, ˝ E., Hetényi, G., Kovács, I., Molinari, I., Süle, B., Szucs, ˝ E., Wesztergom, V., Wéber, Z., the AlpArray Working Group, 2018. AlpArray in Hungary: temporary and permanent seismological networks in the transition zone between the Eastern Alps and the Pannonian basin. Acta Geod. Geophys.

14. Green, D.N., Vergoz, J., Gibson, R., le Pichon, A., Ceranna, L., 2011. Infrasound radiated by the Gerdec and Chelopechene explosions: propagation along unexpected paths. Geophys. J. Int. 185, 890–910.

15. Hedlin, M., Drob, D.P., 2014. Statistical characterization of atmospheric gravity waves by seismoacoustic observations. J. Geophys. Res., Atmos. 119 (9), 5345–5363.