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DEVELOPMENT OF A MODEL FOR CALCULATING THE DILUTION OF PRECISION COEFFICIENTS OF THE GLOBAL NAVIGATION SYSTEM AT A GIVEN POINT IN SPACE

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Abstract*. In this article, a model for calculating the coefficients of dilution of precision of object positioning using the Global Navigation Satellite System is proposed. The proposed model makes it possible to obtain the values of the coefficients of position dilution of precision of a manned aerial object for a certain period of time in a given area. The dependence of the growth of the dilution of precision coefficient on the number of satellites over a given area is established. It is shown that, when the number of satellites over a given area is 4 or less, the value of the coefficient of the position dilution of precision reaches up to or more 20 units. There is provided an example of the application of the presented model in a certain area during a given period of time. It is established that in February 2024, the coefficient of position dilution of precision of the Global Navigation Satellite System in a given area was more than 20 units 18 times. The reason for this is that at a given location, due to the small number of satellites over a given area, it is practically impossible to measure navigation parameter at certain time intervals. This disadvantage occurs when only the Global Navigation Satellite System is used. The model presented for assessing the accuracy of the Global Navigation Satellite System can be used to evaluate the effectiveness of the use of manned aerial objects when they perform humanitarian, evacuation, rescue and logistics activities in a given area.*

Keywords: global navigation system, navigation parameters, satellite position, navigation parameters, coefficient of the dilution of precision

OPRACOWANIE MODELU OBLICZANIA ROZMYCIA WSPÓŁCZYNNIKÓW PRECYZJI GLOBALNEGO SYSTEMU NAWIGACJI W DANYM PUNKCIE PRZESTRZENI

Streszczenie*. W artykule zaproponowano model obliczania współczynników rozmycia precyzji pozycjonowania obiektów z wykorzystaniem Globalnego Systemu Nawigacji Satelitarnej. Zaproponowany model umożliwia uzyskanie wartości współczynników rozmycia precyzji położenia załogowego obiektu powietrznego w określonym przedziale czasu na zadanym obszarze. Określono zależność wzrostu współczynnika rozmycia precyzji od liczby satelitów na danym obszarze. Wykazano, że gdy liczba satelitów na danym obszarze wynosi 4 lub mniej, wartość współczynnika rozmycia precyzji pozycji osiąga wartość większą niż 20 jednostek. Podano przykład zastosowania przedstawionego modelu na pewnym obszarze w określonym przedziale czasu. Ustalono, że w lutym 2024 r. współczynnik rozmycia precyzji pozycji Globalnego Systemu Nawigacji Satelitarnej na danym obszarze przekroczył 20 jednostek 18 razy. Powodem tego jest to, że w danej lokalizacji, ze względu na małą liczbę satelitów na danym obszarze, praktycznie niemożliwe jest zmierzenie parametru nawigacyjnego w określonych odstępach czasu. Ta wada występuje, gdy używany jest tylko Globalny System Nawigacji Satelitarnej. Przedstawiony model oceny dokładności Globalnego Systemu Nawigacji Satelitarnej może być wykorzystany do oceny skuteczności wykorzystania załogowych obiektów powietrznych podczas wykonywania działań humanitarnych, ewakuacyjnych, ratowniczych i logistycznych na danym obszarze.*

Słowa kluczowe: globalny system nawigacji, parametry nawigacyjne, pozycja satelitarna, parametry nawigacyjne, współczynnik rozmycia precyzji

Introduction

Since 2015, the Global Navigation Satellite System (GLONASS), according to official data, has been transferred to the Ministry of the Russian Federation for use. In the period prior to the large-scale invasion of Ukraine by the Russian Armed Forces and since February 2022, GLONASS has been widely used for positioning in space and guidance of air guided weapons at the objects and territories of Ukraine.

Given the large-scale use of air guided weapons by the Armed Forces of the Russian Federation and their guidance at various objects on the territory of Ukraine using GLONASS, it is important to assess the accuracy of the positioning of these weapons in space. Assessing the positioning accuracy of weapons using GLONASS and identifying areas where the quality of their positioning is poor is important for humanitarian, evacuation, rescue and logistics activities without the threat of guidance to these areas by air attack weapons positioned and controlled using GLONASS.

The GLONASS satellites operate above the surface of the globe in three orbital planes with an inclination of 64.8 degrees and an orbit altitude of 19100 km. The GLONASS system is characterized by the fact that the satellites are not synchronized with the speed of the rotation of the globe, which theoretically provides them with functional stability [5]. Thus, it can be stated that this system does not require additional adjustments throughout the entire period of its active life cycle [9].

Therefore, late and incomplete correction can create conditions under which zones are formed where it is practically impossible to accurately measure the navigation parameters of a manned aerial object using GLONASS to establish its location above the surface.

The accuracy of determining the location of an object such as latitude, longitude, and altitude displayed by the receiver of the manned aerial object depends on many factors. The signals transmitted by satellites and received by the receiver are delayed as they pass through the terrestrial atmosphere. The magnitude of the error depends on the state of the ionosphere, which contains free electrons and ions, and the troposphere, which is associated with most weather phenomena.

The analysis of information on the positioning of various aerospace objects in space with the help of global navigation systems built on the basis of the method of mathematical modeling has revealed certain features of their functioning. Namely, it was found that the coefficient of Dilution of Precision (DOP) depends on the number of visible satellites, their closure angles, which are characteristic of artificial urban development or terrain, as well as time parameters and location of the aerial object.

Assessing the accuracy of object positioning using the Global Navigation Satellite System and identifying areas where poor positioning quality is observed are important in the implementation of defense measures of Ukraine. Accordingly, the direct research on assessing the accuracy reduction of the global navigation system at a given point in space is relevant and important in the implementation of defense measures of Ukraine.

1. Literature review

A number of scientific works [2–8, 10–14] are devoted to the issues of determining and analyzing the navigation parameters of global navigation satellite systems, assessing their accuracy and applying these parameters to navigate objects at a given point in space.

In work [12] it is noted that the problem of accuracy reduction can lead to unnecessary deviations from the routes of unmanned aerial vehicles and increase the probability of their collision, which is a critical factor for safe navigation. To overcome the shortcomings, in this article, the hybrid path planning algorithms that take into account the accuracy of a user positioning are proposed.

The comprehensive analysis of the effectiveness of loosely coupled navigation systems, including augmentation methods, was performed in [2, 15]. And these articles point to several open research questions in this area.

In [8] the fault modes of integrated navigation systems, taking into account multipath, which is considered to be the dominant source of navigation errors in the urban environment, are analyzed.

The scientific article [7] highlights the experimental verification of the influence of errors in determining the coordinates using selected receivers and distorted signals generated by the simulator.

In works [6, 14] the inertial navigation systems with additional navigation sensors are considered to create a solution that provides accurate positioning. The accuracy, size and weight of the system, the amount of electricity required to operate the system, the cost of the system, and the compatibility of the system with other surveying and mapping equipment are taken into account. In addition, it is important to consider the level of support offered by the manufacturer, the quality of the user interface, and the availability of training and technical documentation. The new Ekinox Micro [6] from SBG Systems claims to be a miniature and highly efficient GNSS-based inertial navigation solution.

Combining a high-performance tactical MEMS inertial sensor with a quad-antenna GNSS receiver, the Ekinox Micro is the logical choice for mission-critical applications. It complies with MIL-STD-461, MIL-STD-1275, and MIL-STD-810 standards, ensuring reliable and accurate performance in even the harshest environments.

In [13], the Japanese Guasi-Zenith Satellite System, the Indian Regional Navigation Satellite System, along with GPS satellites and Galileo satellites are considered. The accuracy of the multiglobal navigation satellite model is verified. Using the advantages of being located in the Asia-Australia area, this research provides an instantaneous analysis on ambiguity resolution and positioning performance. The formal measurement results for baselines located in different grids covering Australia, part of the Pacific Ocean, the Indian Ocean, and Asia are shown and discussed, and hence an empirical analysis is presented for two baselines in Perth, Australia.

Compared to the individual cases, for the Perth baselines, it is shown that combining L5 signals from the GPS/Galileo/GZSS/IRNSS global navigation satellite systems significantly improves the accuracy and positioning efficiency. While the average single-system performance is less than 50% even with a low elevation angle of 10 degrees, the combination of all four systems increases the accuracy to more than 95% at the maximum elevation angle of 40 degrees.

With a 40-degree elevation angle, using satellites from a single system fails to provide meaningful positioning solutions for more than 8 hours during the test day. Based on the positioning results, it is possible to obtain fixed standard deviations at the ambiguity level from mm to cm for almost a full day when combining all four navigation systems.

In addition to this, simulations have also been performed for receivers with a larger signal standard deviation, i.e., low-cost receivers or receivers located in environments with greater multipath.

Work [1] indicates that one of the main challenges faced by urban air mobility and the safe integration of unmanned aerial systems into urban airspace is the need for reliable navigation systems.

It is known that navigation satellite systems are usually the main source of positioning for most air and ground vehicles and weapons, as defined in [3]. This paper notes that their performance is often insufficient in difficult conditions. It is emphasized that when improving existing and developing new similar systems, their navigation strategy should take into account the impact of artificial urban structures and natural terrain on navigation efficiency through simulation studies of plowed areas of possible application.

Works [10, 11] outline the basic theoretical provisions of building navigation systems based on mathematical modeling. At the same time, there are no considerations of such aspects as under what situations and conditions the given accuracy of a global satellite navigation system will not be ensured.

The analysis of the above literature [2–8, 10–14] demonstrates that insufficient attention has been paid to the analysis of navigation parameters of global navigation satellite systems, assessment of their accuracy and application of these parameters for navigation. Also, the issues of identifying areas and zones where, under certain conditions, low quality positioning of airborne objects will be observed have not been sufficiently studied. These circumstances form a new scientific and applied task. The solution to which is aimed at assessing the accuracy of object positioning in space using a global navigation system and identifying areas where such accuracy is low.

2. Researches methodology

The purpose of the article is to reduce the effectiveness of the use of airborne objects and high-precision weapons that are positioned in space using the Global Navigation System at a given point in space over a certain period of time. Such a reduction in efficiency can be achieved by assessing the accuracy of positioning in space of these objects using the Global Navigation Satellite System and establishing areas where low quality of their positioning will be observed. This, in turn, will ensure that the defense measures of Ukraine can be carried out without the threat of the forces involved to be detected and destroyed by high-precision weapons of the Armed Forces of the Russian Federation, which are positioned and controlled in space using the Global Navigation Satellite System.

To achieve the aim of the research it is necessary to:

- to define and generalize the relationship between the parameters for assessing the accuracy of object positioning in space using the Global Navigation Satellite System;
- to develop a holistic model for calculating the dilution of precision coefficients of object positioning using the Global Navigation Satellite System;
- using the methods of mathematical modeling based on the developed model, to calculate the coefficients of the position dilution of precision of the objects in a given area for a certain period of time.

The object of research is the process of assessing the accuracy of object positioning using the Global Navigation Satellite System at a given point in space. The main hypothesis is that only one global navigation system such as GLONASS is used, and no other systems are used.

To conduct the research, a model of the existing Global Navigation Satellite System was used, which is used by the Russian Federation to position precision weapons in certain areas over a set period of time. The research was conducted by mathematical modeling.

3. The research results

3.1. Analysis of parameters

GLONASS satellites move in 3 planes with 8 satellites in each of them. This is shown in Fig. 1

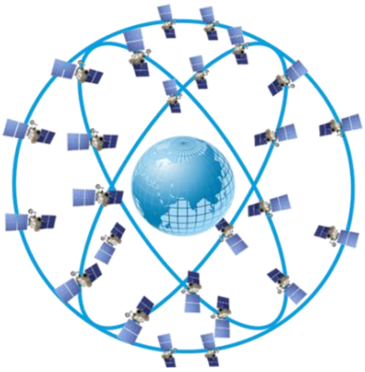


Fig. 1. GLONASS scheme [16]

The GLONASS system is based on measuring the distance from the receiver antenna at an object to the navigation satellites, the location of which is known with great accuracy. Knowing the distances to several satellites of the system, the position of the object in space is calculated using conventional geometric constructions.

The method of measuring the distance from the satellite to the receiver antenna is based on determining the speed of radio wave propagation. Each satellite of the navigation system emits precise time signals using a synchronized clock. When the satellite receiver is operating, its clock is synchronized with the system time, and when the satellite signals are subsequently received, the delay between the emission time contained in the signal itself and the time the receiver antenna receives the signal is calculated. Based on this information, the navigation receiver calculates the coordinates (Fig. 2).

Fig. 2. Object positioning scheme using GLONASS [1]

Error sources also include satellite and receiver clock errors, orbital or ephemeral errors, multipath errors, and receiver noise.

The total error (δ) is the total error budget that affects pseudorange. It is the square root of the sum of the squares of the individual displacements. Using a calculation similar to the one mentioned above, the PDOP (Position Dilution of Precision) coefficient can be used to determine the positional error that would result from a specific value at the one sigma level (68.27%).

For example, assuming a PDOP coefficient of 1.5 and δ = 6 m, the positional accuracy would be 9 m at 1 sigma (68.27%).

In other words, the standard deviation of the position is the Dilution of Precision coefficient multiplied by the square root of the sum of the squares of the individual displacements (δ).

Multiplying the values will provide a 95% reliability level in estimating the error, which will be 18 meters.

Instead of considering the errors individually, all of the above errors can be summarized in a single value called the total error.

The total error will be an indicator of the distance, which we will consider identical and independent for all satellites and which can be calculated by taking the square root of the sum of the squares of individual errors.

The total error, for example, in Table 1 is calculated as follows, in meters:

$$\delta = \sqrt{3^2 + 3^2 + 4^2 + 0.7^2 + 1.4^2 + 0.8^2} = 6.09$$

According to Table 1, there is nothing the user can do to reduce the total error, since most types of errors are beyond his or her control.

The contribution of these errors can be represented as the sum of the errors shown in Table 1.

Table 1. Types and magnitudes of errors of global navigation systems

Error type	Magnitude of the error, in meters	Segment
Satellite position	3.00	A signal in space
Time	3.00	A signal in space
Ionosphere	4.00	Atmosphere
Troposphere	0.70	Atmosphere
Multipath	1.40	Receiver
Receiver	0.80	Receiver
Total error, δ	6.09	

Thus, there is a contradiction that needs to be resolved by means of a new methodological approach to assessing the Dilution of Precision coefficients of the global navigation system and the use of new scientific results.

3.2. Calculation model

To calculate the DOP (Dilution of Position) coefficients, consider unit vectors from the receiver to the satellite of the global navigation system i:

$$\left[\frac{(x_i - x)}{R_i}, \frac{(y_i - y)}{R_i}, \frac{(z_i - z)}{R_i}\right]$$

$$R_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \qquad (1)$$

In formula (1), the coordinates x, y, z determine the position of the receiver. In this case, the coordinates x_i, y_i, z_i determine the position of one of the satellites of the global navigation satellite system i.

The research analysis shows that the ideal location of the four satellites would be one directly above the receiver, and the others would be 120° apart in azimuth near the horizon. With this distribution, the DOP will be about 1 (Table 1), which is the lowest possible value. In practice, the lowest DOP is usually about 2.

In global satellite navigation systems, angles play an important role. With four satellites, three of which are on the horizon and one directly overhead, a low accuracy value is ensured. However, it is difficult to track satellites that are right at the horizon. They need to be above 10 or 15 degrees from the horizon to try to minimize the influence of the ionosphere. When the DOP ratio exceeds the maximum limit at a certain location, it indicates that an unacceptable level of uncertainty exists for a certain period of time and this period is called a failure. This expression of uncertainty is also useful for interpreting measured baselines.

The matrix A of the global navigation system pseudorange measurement can be represented as (2):

$$A=\begin{bmatrix} \frac{(x_1-x)}{R_1} & \frac{(y_1-y)}{R_1} & \frac{(z_1-z)}{R_1} & 1 \\ \frac{(x_2-x)}{R_2} & \frac{(y_2-y)}{R_2} & \frac{(z_2-z)}{R_2} & 1 \\ \frac{(x_3-x)}{R_3} & \frac{(y_3-y)}{R_3} & \frac{(z_3-z)}{R_3} & 1 \\ \frac{(x_4-x)}{R_4} & \frac{(y_4-y)}{R_4} & \frac{(z_4-z)}{R_4} & 1 \end{bmatrix} \quad (2)$$

The first three elements of each row of the matrix A are the components of the unit vector from the receiver to the global navigation system satellite.

The last element of each row refers to the partial derivative of the pseudorange with respect to the receiver clock shift.

Represent the matrix G as a covariance matrix obtained from the normal matrix by the least squares method:

$$G=(A^T A)^{-1}$$

or in the general case, present it:

$$G=(L_x^T(L_d C_d L_d^T)^{-1}-L_x)^{-1}$$

where: L_x is the Jacobian of the residual measurement equations of the receiver $f_i\left(\bar{x},\bar{d}\right)=0$, with respect to the unknowns $\bar{x}$; L_d is the Jacobian of the residual measurement equations of the receiver with respect to the measured quantities $\bar{d}$; C_d is the correlation matrix of the noise in the measured quantities.

For this case, the residual measurement equations are:

$$\bar{x}=(x,y,z,t)^T,\ \bar{d}=(t_1,t_2,t_3,t_4)^T,\ t=ct_i,$$

$$R_i=|t_1-t|=\sqrt{(t_i-t)^2},$$

$$f_i\left(\bar{x},\bar{d}\right)=\sqrt{(x_i-x)^2+(y_i-y)^2+(z_i-z)^2}-\sqrt{(t_i-t)^2},$$

$$L_x=A,\ L_d=-I$$

and the measurement noise for different t_i are assumed to be independent, making $C_d = 1$.

These formulas for G arise from applying a linear unbiased estimator to a linearized version of the receiver measurement residual equations with respect to the current solution:

$$\Delta x=-G*(L_x^T(L_d C_d L_d^T)^{-1} f)$$

except when C_d is the noise covariance matrix used to calculate the DOP coefficients to obtain the relative error. When C_d is the noise covariance matrix, G is the estimate of the noise covariance matrix in the unknowns due to noise in the measured quantities.

This estimate is obtained using the second-moment first-order uncertainty quantification technique. It is used when the distribution of the input noise is assumed to be Gaussian, or the standard deviations of the measurement noise are small relative to the rate of change of the output signal.

For the residual equations, the measurement of signal arrival time or range measurement can be represented by a weighting matrix $P=\left(L_d C_d L_d^T\right)^{-1}$, which will simplify the matrix to the form:

$$G=\begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t^2 \end{bmatrix}$$

The weighting matrix P simplifies the matrix due to the fact that all the equations of the measurement residual are arrival time (pseudorange) equations.

Avoiding time measurements will actually increase the accuracy of the geolocation solution.

Now, since the location is derived from a three-dimensional (3D) solution, look at several components of DOP that are used to estimate the uncertainty in the location components.

There is Horizontal Dilution of Precision (HDOP) and Vertical Dilution of Precision (VDOP), where the uncertainty of a solution for positioning is separated into horizontal and vertical components, respectively. When both the horizontal and vertical components are combined, the uncertainty of the 3D positions will be the Position Dilution of Precision (PDOP).

At the same time, the Time Dilution of Precision (TDOP) indicates the uncertainty of the clock. The Geometric Dilution of Precision (GDOP) is a combination of all of the above. The relationship between the geometry of the satellite configuration and GDOP is shown in Table 2. At the same time, GDOP results of more than 20 units should be discarded [2, 17].

The Relative Dilution of Precision (RDOP) takes into account the geometry of the satellite configuration, the number of receivers, the number of satellites being serviced, and the duration of the observation.

PDOP combines both vertical and horizontal components. Thus, the better the geometry, the better the overlap of satellite bands, the smaller the dilution of precision value, and the more accurate the resulting position value.

Table 2. Relationship between satellite configuration geometry and GDOP

DOP value, r.u.	Accuracy	Description
≤1	Ideal	It is recommended for use in systems that require the maximum possible accuracy during their operation.
2–3	Excellent	Sufficient accuracy to use the measurement results in highly sensitive equipment and applications.
4–6	Good	The recommended minimum for decision-making based on the results obtained. The results are used for precise navigation guidance.
7–8	Average	The results are used in calculations, but it is recommended to improve the accuracy, for example, to go to a more open place.
9–20	Below average	The results are used for rough approximate location determination.
21–50	Poor	The output accuracy is very low. Normally, such results should be discarded.

Dilution of Precision (DOP) is described in the form of quantitative indicators of individual measurements, such as [4]:

$$HDOP=\sqrt{\sigma_n^2+\sigma_e^2}\ \text{(Horizontal DOP)}, \quad (3)$$

where – σ_n, σ_e – root mean square deviation of Horizontal DOP

$$VDOP=\sqrt{\sigma_u^2}\ \text{(Vertical DOP)}, \quad (4)$$

$$PDOP=\sqrt{\sigma_x^2+\sigma_y^2+\sigma_z^2}\ \text{(Position (3D) DOP)}, \quad (5)$$

$$TDOP=\sqrt{\sigma_t^2}\ \text{(Time DOP)}, \quad (6)$$

$$GDOP=\sqrt{PDOP^2+TDOP^2}=\sqrt{trG}\ \text{(Geometric DOP)} \quad (7)$$

At the same time, the derivatives are defined as:

$$GDOP=\sqrt{EDOP^2+NDOP^2+VDOP^2+TDOP^2} \quad (8)$$

$$HDOP=\sqrt{EDOP^2+NDOP^2} \quad (9)$$

$$PDOP=\sqrt{EDOP^2+NDOP^2+VDOP^2} \quad (10)$$

The users of most navigation system receivers can set a PDOP value to ensure that no data is recorded if the PDOP exceeds the set value. A typical PDOP value is 6. As the PDOP increases, the accuracy of the pseudorange positions deteriorates, and as it reduces, it improves [14, 15].

The effect of satellite geometry on the position error is the Geometric Dilution of Precision (GDOP) and is interpreted as the ratio of the position error to the range error [4, 16].

It is possible to represent a pyramid formed by lines connecting the satellites to the receiver at the top of the pyramid. The larger the volume of the pyramid, the smaller the geometric dilution of precision (GDOP); the smaller its volume, the higher the GDOP value will be.

Thus, as the number of satellites increases, the GDOP value improves [4, 10].

Furthermore, the noise error of the incoherent delay tracking scheme of the transmission system parameter, which has a root mean square deviation given by the following expression, was taken into account in the research [17]:

$$\sigma = \tau_S \sqrt{\frac{B_t}{P/N_0} + \frac{B_t B_r}{(P/N_0)^2}} \tau_S \sqrt{\frac{B_t}{P/N_0} + \frac{B_t B_r}{(P/N_0)^2}}$$

where S is the duration of the elementary symbol of the transmission system parameter; B_t is the one-way bandwidth of the delay tracking scheme; B_r is the one-way bandwidth of the intermediate frequency path; P/N_0 is the ratio of signal power to the spectral density of noise at the receiver input.

Thus, the range of errors in estimating the pseudo-distance is 0.5...30 m, and the pseudo-velocity is 0.1...10 m/s [17].

The calculations performed by expressions (3-10), at the root mean square deviations σ_x, σ_y, and σ_z, taken in the values of 0.5...30 m, which represent the errors of the receiver position at a given point of the terrain in the directions to the north, east, and altitude, respectively, show that at least five visible satellites are needed for the integrity of horizontal positioning to ensure HDOP < 5.581 [2].

Seven visible satellites are required to provide HDOP < 2.291, eight visible satellites are required to provide HDOP < 1.534 [2].

HDOP below 1.123 can be achieved if at least ten satellites are visible [2].

A certain number of visible satellites is required for the integrity of the vertical positioning.

Based on these results, the levels of indirect protection based on DOP can be determined by using the altitude limit and satellite visibility to describe the positioning integrity.

The DOP coefficients are functions of the diagonal elements of the covariance matrix of parameters expressed in a global or local geodetic system.

3.3. Calculation of coefficients

The modeling of the values of the dilution of precision coefficients of object positioning in a given area for a certain period of time and obtaining actual calculations of the values under different options were carried out under the following condition. The accuracy of determining the coordinates of the GLONASS navigation system in a given area at a specific time for February 2024 is investigated.

The accuracy of multiple satellites with respect to a receiver depends on the relative position of the satellites. When the visible navigation satellites are close together in the sky, the geometry is said to be weak and the DOP value is high; when they are far apart, the geometry is strong and the DOP value is low.

Thus, a low DOP value represents better positional accuracy due to the greater angular distance between the satellites used to calculate the position of the device. Other factors that can increase the effective DOP are obstacles such as mountains or tall buildings in the vicinity.

The geographical coordinates are determined and the required parameter values are calculated in the position set for each option (Table 3). Based on the calculations, a conclusion is made about the possibility of using positioning information.

The considered mathematical expressions (3-10) provide the dependencies of the PDOP coefficient of the GLONASS Global Navigation System in a given area for a certain period of time, taking into account the values of the root mean square deviations σ_x, σ_y, σ_z, and σ_t.

In the process of modeling and calculating the coefficients of position dilution of precision of objects, the following patterns were established. Table 3 shows that in February 2024, the accuracy of the GLONASS system was very low 18 times (DOP value was more than 20).

For example, on 02.02.2024 at 05:00, the GDOP value was 2.23, which was determined by the number of visible satellites and the value of the root mean square deviations. The results of the GDOP calculations carried out by the method of mathematical modeling according to expressions (3-10), taking into account the characteristics of accuracy and the number of satellites over a given area formed for certain dates and times, are given in Table 3 [16, 17].

The considered mathematical expressions make it possible to analyze the change in PDOP, for example, of the GLONASS global navigation system.

The calculations were carried out for the period of February 2024 near the city of Avdiivka (Ukraine) (Fig. 4), with coordinates: latitude 48º9'11.7379", longitude 37º44'31.7651".

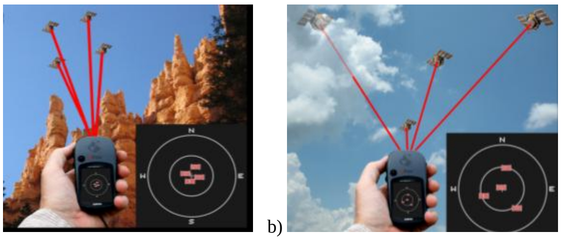
In the process of modeling and calculating the dilution of precision coefficients of object positioning, the following patterns were established. It can be seen from Table 3, 18 times in February 2024, the accuracy of the GLONASS system was very low (DOP value was more than 20). This means that at a given point of the terrain in some time intervals it is almost impossible to measure navigation parameters using only the GLONASS system.

The calculations revealed that in February 2024, the GLONASS system failed to provide the specified location accuracy 18 times (Table 3).

Sometimes such cases occurred 2-3 times a day. For example, there were 3 cases of poor navigation system accuracy on February 14 and 22, 2024.

Unfavorable location of navigation satellites: all of them are too close to each other, which increases GDOP (reduces accuracy) is shown in Fig. 3a.

Favorable satellite location gives a low GDOP and high accuracy, Fig. 3b.



a) b)

Fig. 3. Geometry of satellite grouping: a) unfavorable location of navigation satellites, b) favorable satellite location [2]

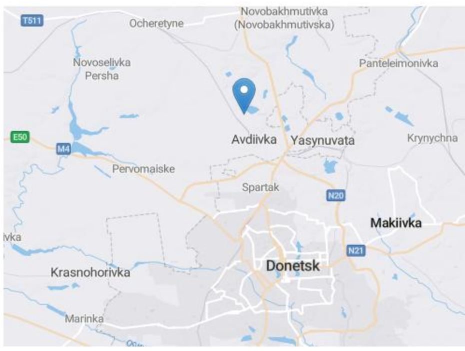


Fig. 4. Map in the area of Avdiivka (Ukraine), showing the area with coordinates: latitude 48º9'11.7379", longitude 37º44'31.7651" [16]

In the context of hostilities in eastern Ukraine, the armed forces of the Russian Federation widely use the Global Navigation Satellite System (abbreviated as GLONASS), which consists of 24 satellites (Fig. 5 a, b).

Table 3. Indicators of the GLONASS accuracy reduction in the area of Avdiivka (Ukraine), showing the area with coordinates: latitude 48º9'11.7379", longitude 37º44'31.7651"

No	Date	Time, s	Impact of satellite geometry GDOP, r.u.	Time Dilution of Precision, r.u.	Position Dilution of Precision, r.u.	Horizontal Dilution of Precision, r.u.	Vertical Dilution of Precision, r.u.	Total error, r.u.
1	02.02.2024	05.00	2.23	1.02	1.98	1.32	1.48	20
2	05.02.2024	14.10	–	–	–	5.64	–	–
3	05.02.2024	14.20	2.57	1.28	2.23	1.35	1.78	20
4	06.02.2024	04.40	3.84	2.07	3.24	2.04	2.51	20
5	07.02.2024	04.30	–	17.32	–	2.11	–	–
6	07.02.2024	04.40	2.18	0.99	1.94	1.28	1.46	20
7	14.02.2024	04.00	–	16.75	–	–	–	–
8	14.02.2024	04.10	3.81	2.05	3.2	2.02	2.49	20
9	14.02.2024	12.00	3.4	1.76	2.91	1.8	2.29	20
10	15.02.2024	04.00	–	17.15	–	2.37	–	–
11	15.02.2024	04.10	2.61	1.29	2.27	1.42	1.78	20
12	18.02.2024	05.20	–	–	–	5.87	–	–
13	18.02.2024	05.30	2.33	0.96	2.13	1.63	1.38	20
14	22.02.2024	03.30	–	–	–	15.43	–	–
15	22.02.2024	03.40	3.76	2.03	3.17	1.99	2.47	20
16	22.02.2024	11.30	3.37	1.75	2.88	1.78	2.26	20
17	23.02.2024	03.30	–	16.86	–	2.69	19.89	–
18	23.02.2024	03.40	2.59	1.28	2.25	1.39	1.77	20

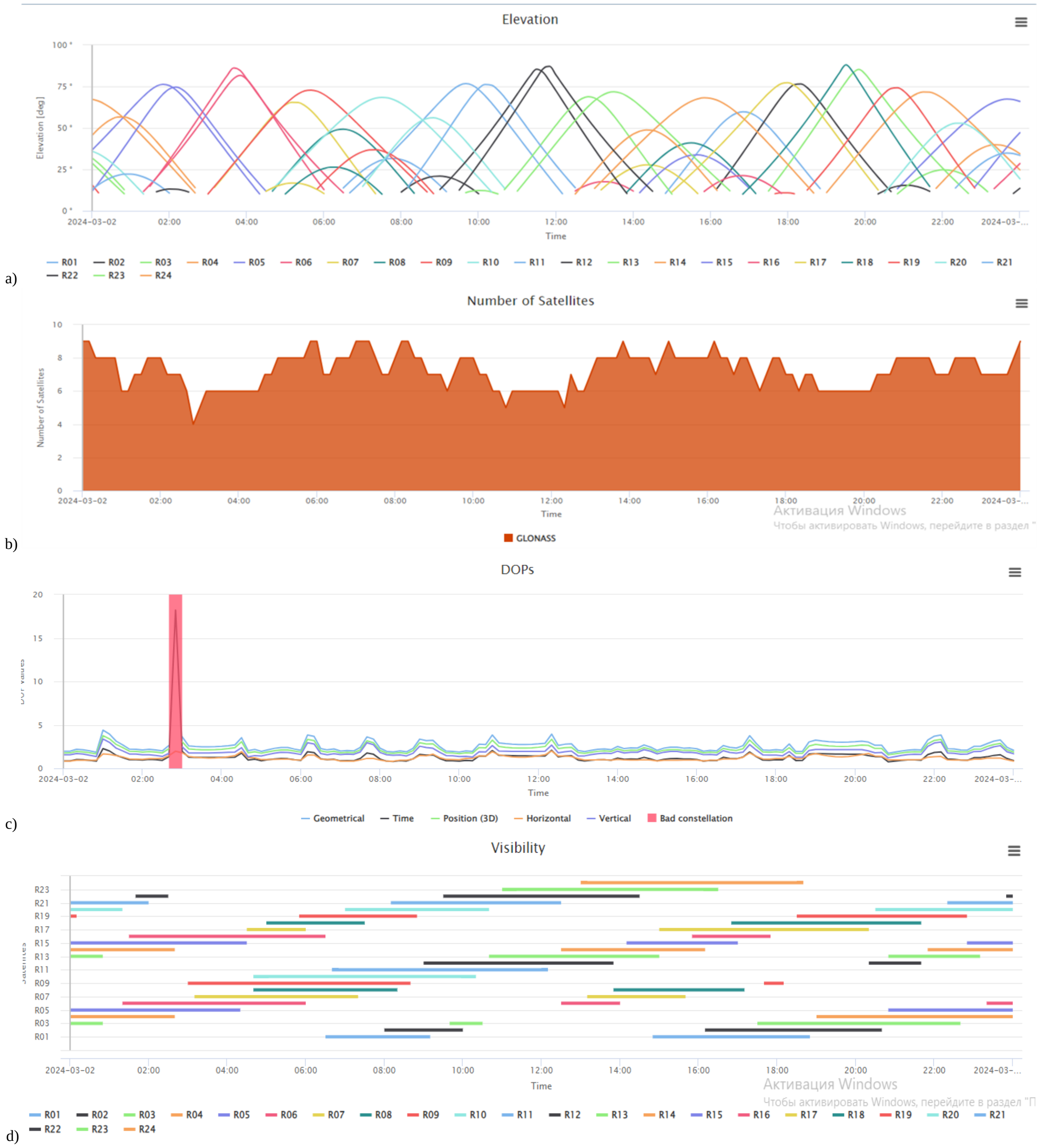


Fig. 5. An example of calculating GLONASS parameters on 23.02.2024 in the area of Avdiivka (Ukraine), with coordinates: latitude 48º9'11.7379", longitude 37º44'31.7651": a, b – satellite position at a particular time; c, d – GLONASS accuracy indicators over time and satellite visibility

Navigation accuracy depends on the number of satellites over a point on the terrestrial surface and can be significantly degraded due to the geometric position of the satellites relative to the user Fig. 5 c, d and also due to the angles of closure within the line of sight.

In the first simulation, a reference model of the effect of DOP on accuracy was established. The positioning results were obtained and statistically analyzed at a boundary height of 5°, which corresponds to open sky conditions. Test constellations (Fig. 6) with different DOP values were identified in the simulator, as shown, and navigation messages were created for each of them.

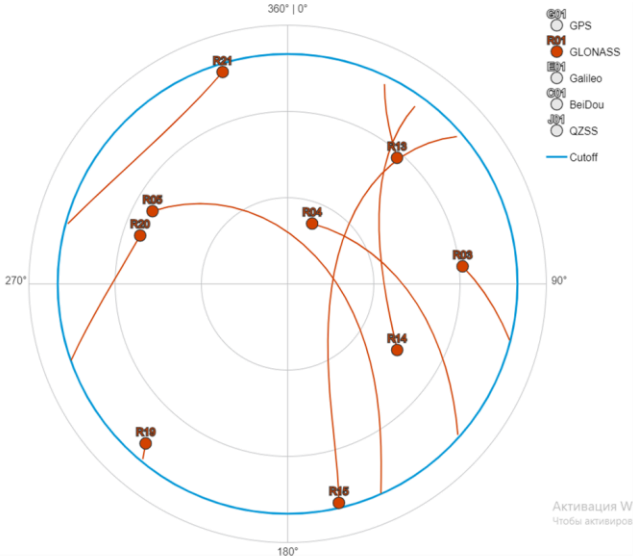


Fig. 6. Visibility of GLONASS satellites at a particular moment in time [16]

Since the DOP is affected by the change in the number of satellites (Fig. 7) available to the receiver, the test constellations were limited to four visible satellites. Other satellites are disabled for each test to eliminate the effect of the number of visible satellites.

The use of DOP ratios to characterize accuracy or availability is mostly limited to availability analysis and does not include integrity requirements.

In this case, an approach is used that can be useful when information is not available. Alternatively, it is possible to focus on integrity analysis, using DOP ratios and height and visibility criteria.

One of the key innovations of this approach to integrity monitoring is the proposal and use of DOP-based indirect protection levels as a replacement for standard position error-based protection levels.

At the same time, the DOP coefficients can be extracted from the receiver output signals while moving, unlike untraceable position errors.

The visibility of GLONASS satellites at a particular time and their positioning relative to the surface of the Earth at a particular time are shown in Figures 5 and 6.

If the navigation system in a given area at a given time does not provide the required accuracy of coordinate determination, then high-precision weapons cannot be used effectively. An error in determining the coordinates greater than the permissible value (more than 20) leads to a decrease in the effectiveness of the use of destruction means by the enemy.

The cases when the error in determining the coordinates is greater than the permissible value will be of interest to us. For example, there will be 18 such cases for the period of February 2024 (Table 3).

The analysis of Fig. 5. shows that when there are 4 GLONASS satellites above a point of the surface of the Earth, the accuracy will be poor (DOP more than 20). A large error can also be due to horizontal dilution of precision, for example, on 02.18.2024 at 05.20 a.m. – the horizontal dilution of precision will be 5.87. Also, for example, a large error will be on 02.14.2024 at 04.00 a.m. – the time dilution of precision will be 16.75.

The simulated operating conditions of the navigation system make it possible to obtain data on the accuracy of the navigation system at a given point in the area. Accordingly, it is expedient to use the received information in practice in the interests of evacuation operations, rescue operations, humanitarian missions, etc.

The adequacy of the model proposed in this article was assessed by comparing the calculated data with the experimental data obtained over several days during an experiment to determine the accuracy of the coordinates of satellites that were within the radio range over a given area during a given period of time.

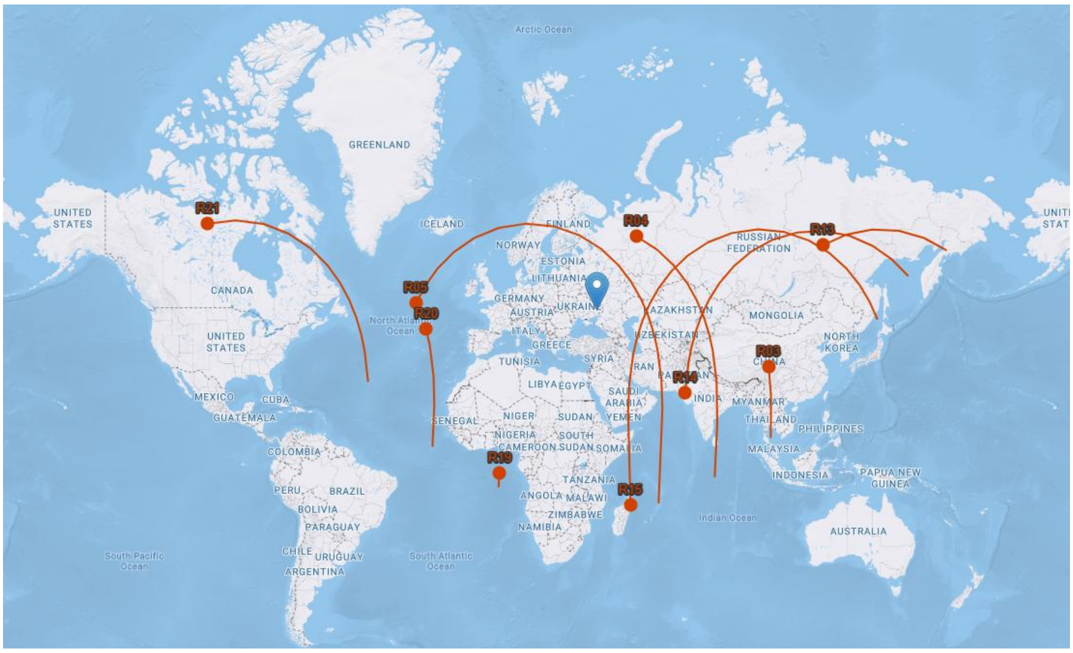


Fig. 7. Positioning of GLONASS satellites relative to the surface of the Earth at a given time [16]

4. Discussion of the results

The obtained results of assessing the accuracy of object positioning using the Global Navigation Satellite System at a given point in space depend on the number of visible satellites (Fig. 5).

The peculiarities of the proposed method and the results obtained in comparison with the existing ones are the novelty of the proposed approach depending on the number of satellite positions and the approximate position of the receiver. In contrast to the method presented in [12], where hybrid algorithms for predicting the trajectory of an object are proposed, this research considers the location determination at a given point over a long period of time, taking into account the accuracy of object positioning.

Moreover, this approach, in contrast to the comprehensive analysis of the efficiency of loosely coupled navigation systems considered in works [2, 15], makes it possible to predict the dominant sources of navigation errors at a particular point of the area.

The practical significance of the proposed model, compared to the one presented in [7], is the application of the developed highly efficient navigation solution that functions by reproducing real positioning conditions.

The developed model for assessing the accuracy of the Global Navigation Satellite is adequate for assessing the threats of the use of high-precision weapons by the enemy when performing humanitarian, evacuation, rescue and logistics activities in the designated area.

To the shortcomings of the presented research should be considered the lack of consideration of the peculiarities of assessing the accuracy of object positioning using other global navigation satellite systems.

A further direction of research is the proposal to complement the integrity measurements based on DOP parameters with other parameters specific to the immediate environment. This will enable to assess the integrity in a specific environment, which can be used to make decisions on mitigation measures in cases of observed failures of navigation performance.

In general, the dilution of precision coefficients can be interpreted as the inverse of the volume of the tetrahedron formed from the satellites and the position of the receiver. Thus, the best geometric situation for positioning a point is when the volume of the shape is close to the maximum value. At the same time, the lower the value of the DOP coefficient, the higher the accuracy of the positioning results.

It is shown that the DOP coefficient varies depending on the time of day and geographical location, while the developed model makes it possible to calculate DOP depending on the number of satellite positions and the approximate position of the receiver.

The value of the dilution of precision coefficients can be useful when planning the use of manned aerial vehicles for evacuation, rescue operations, humanitarian missions, etc.

The article investigates the coefficients of dilution of precision (DOP) under nominal and complex conditions of positioning of a manned aerial object in the given areas of task performance.

The data obtained on the positioning of an object in the simulated environment using a software receiver made it possible to propose an approach to monitoring based on a joint consideration of the observed satellites and environmental parameters. It is demonstrated that the DOP coefficients, when considered together with the number of visible satellites and the maximum altitudes typical of the military environment, contain valuable information for assessing the accuracy of object positioning.

It is shown that the DOP coefficients, when considered together with the number of visible satellites and the maximum altitudes typical for the military environment, contain valuable information for assessing the accuracy of object positioning.

This enables to generate indirect integrity indicators based on the altitude limit and satellite visibility, which can be used to plan the trajectory of manned aerial objects and automatically guide them to the areas of mission execution.

The above proposed and tested software allows to form various configurations of satellite navigation systems and to obtain estimated values of the coefficients for assessing the accuracy of determining the coordinates of an object in space.

In addition, the proposed model makes it possible to generate scenarios of sudden failures of GLONASS satellites, as well as to predict the accuracy of GLONASS in conditions of limited visibility of navigation satellites from its composition.

5. Conclusions

1. The article deals with the issue of assessing the positioning accuracy of objects using the Global Navigation Satellite System.

It has been established that in the context of the widespread use of manned aerial objects and when correcting their location using the Global Navigation Satellite System, it is important to assess the accuracy of their positioning in space. Assessing the positioning accuracy of manned aerial objects using the Global Navigation Satellite System and identifying areas where poor positioning quality is observed are important when performing humanitarian and logistics activities involving them.

2. A model for calculating the coefficients of position dilution of precision of manned aerial objects using the Global Navigation Satellite System is proposed.

The presented model makes it possible to obtain the values of the coefficients of the object positioning accuracy reduction for a certain period of time in a given area.

The dependence of the growth of the dilution of precision coefficient on the number of satellites over a given area is established. It is shown that, when the number of satellites over a given area is 4 or less, the value of the coefficient of position dilution of precision reaches a value of more than 20 units. This indicates a low accuracy of object positioning in a given area.

3. An example of the application of the presented model is given. According to which, in February 2024, the coefficient of position dilution of precision of aerial objects using the Global Navigation Satellite System reached a value of more than 20 units 18 times. This is due to the circumstances according to which, at a given point of the area in some time intervals, it is practically impossible to measure navigation parameters using only the Global Navigation Satellite System.

4. The model for assessing the accuracy of the Global Navigation Satellite System presented in this article can be used in the process of assessing the positioning accuracy of aerial objects when performing humanitarian, evacuation, rescue and logistics activities in the designated area.

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