Розглянуто математичну модель точності локальної радіонавігаційної системи, утвореної на базі мережі псевдосупутників. Встановлено рівень впливу геометрії структури на точність визначення вектора стану споживача. Промодельовано поле точностних характеристик для структур різної топології. Запропоновано методику формування оптимальної структури за критерієм точності навігації з урахуванням можливих збоїв у роботі окремих елементів

Ключові слова: псевдосупутник, радіонавігаційна система, вектор стану споживача, точність, навігаційний параметр, псевдодалекість

Рассмотрена математическая модель точности локальной радионавигационной системы, построенной на базе сети псевдоспутников. Установлен уровень влияния геометрии структуры на точность определения вектора состояния потребителя. Промоделировано поле точностных характеристик для структур разной топологии. Предложена методика формирования оптимальной структуры по критерию точности навигации с учетом возможных сбоев в работе отдельных элементов

Ключевые слова: псевдоспутник, радионавигационная система, вектор состояния потребителя, точность, навигационный параметр, псевдодальность

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THE MODEL OF ACCURACY OF A LOCAL RADIO NAVIGATION SYSTEM CONSIDERING UNSTABLE PERFORMANCE OF INDIVIDUAL ELEMENTS

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1. Introduction

Global Navigation Satellite System (GNSS) have lately become practically the only method of the positioning of moving objects. However, GNSS like any other complex technical system cannot be 100 % protected from unauthorized access by outside (terrorist) organizations and individuals. Therefore, a general problem is developing such a reserve system (local), which could replace it in the case of emergency in a minimal time and with minimal expenses for re-equipment of consumers. In this case we propose setting up alternative local radio navigation systems (LRNS) based on pseudo satellites – pseudolites (PL) [1–3]. The structure of such a system may consist of a segment of air (APL) and ground (GPL) pseudolites, a network of control stations (CS) and a consumer segment (Fig. 1). The GPL network creates a continuous navigation field for consumers above the ground (planes, helicopters and, in fact, air pseudolites). The APL network creates similar field for ground (terrestrial) consumers.

As for any navigation system, a topical issue for LRNS is a problem of the accuracy of determining the location of moving objects, and since in addition to the location determining these systems allow defining parameters of speed, then, in general, we can talk about the state vector of the consumer. The given problem acquires even greater relevance for the systems of special purpose (military, emergency services, etc.), which operate under challenging conditions of possible degradation of the structure due to intentional influence from the outsiders (terrorist organizations), since the change in the structure will certainly affect the accuracy of navigation.

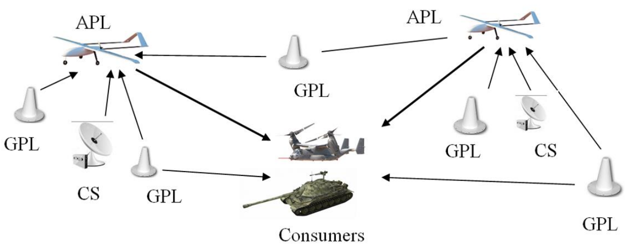

Fig. 1. LRNS structure

2. Analysis of scientific literature and the problem statement

The issue of the accuracy of determining the state vector of the consumer in LRNS is given a significant amount of publications. Thus, the paper [4] addresses the issue of constructing antenna devices and assessments of the impact on the accuracy of interfering signals. In this case several scenarios of using local radio navigation are considered: either in the form of additional system for GNSS or autonomously. It is shown that in the case of autonomous use, a positioning accuracy is somewhat reduced while the number of collisions of interference decreases. The paper [5] describes effects of atmospheric phenomena on LRNS, and as a mathematical base of assessment of the accuracy, the Kalman filtering is applied. However, there are certain difficulties in determining the coefficients of filtration, which is caused by fluctuations in accuracy and dependence on the relative position of consumers and transmitters. The paper [6] considers the impact of signal power and non-uniformity in the range of navigation measurements on the accuracy of the navigation. It is stated that when using the pseudolites, the problem of determining the accuracy is enhanced due to possible re-reflections of radio beams and significant changes in power. The articles [7, 8] show the basics of navigation measurements taking into account spatial structure of LRNS. However, the factors of the influence of geometry of spatial structure on the accuracy of navigation are not defined.

The paper [9] considers the model of accuracy of a pseudolite system from the point of view of different variants of its autonomous application. In that case the problem was discovered of the necessity of taking into account the differences in distribution of the signals for GNSS and LRNS in the hardware part of the system through possible distortion of the accuracy characteristics on the side of the consumer. The simulation was performed and the algorithm of reducing possible measurement errors was proposed. In [10, 11] the authors proposed an original algorithm of the coordination of time scales in the network of pseudolites and reducing the errors in accuracy through the lack of synchronization of individual pseudolites in the network. The article [12] analyzed and simulated the impact of troposphere on the accuracy of defining the state vector of the consumer in LRNS. Quantitative characteristics of the influence and coefficients of signals delay were defined depending on the distance between a pseudolite and the consumer, atmospheric pressure, temperature and humidity. The paper [13] suggested a model of accuracy for asynchronous variant of constructing a system based on the measured method of the least squares. The accuracy of defining coordinates according to this variant was simulated and the advantages of asynchronous approach to the local navigation systems of meter accuracy were proven.

However, in all these sources LRNS is regarded as an open system of continuous action – analog of satellite radio-navigation systems. Such an approach only partially describes LRNS because it does not take into account a possibility of failure (destruction, intentional damage) of individual elements – pseudolites. The loss of individual elements will definitely lead to reducing the accuracy or the termination of navigation at all. This explains the relevance of the task to develop a methodology of evaluation the accuracy of LRNS considering requirements for stability of its performance.

3. The purpose and objectives of the study

The aim of this work is to develop a mathematical model of the accuracy characteristics of LRNS considering the instability in the functioning of its individual elements.

To achieve the specified goal, the following tasks and research are to be performed:

– to develop a model of accuracy of a local radio navigation system, the base of which will be formed by the topology of its structure;

– based on the received model of accuracy, to develop a model of spatial structure of LRNS, which would take into account possibility of unstable operation of individual elements;

– to develop a methodology for forming the structure of a local radio navigation system considering the instability of the functioning of individual elements.

4. The base model of the accuracy of a local radio navigation system

As the navigation parameter of LRNS, also of GNSS, we apply pseudo ranges (PR) to AS. The concept of geometric factor (GF) is used to assess the magnitude of the decrease in the accuracy of determining the location of the consumer relative to the accuracy of determining the navigation parameter. The value of GF indicates the number of times that the mean-square error (MSE) of determining the coordinates of the consumer will exceed the MSE of defining PR. To form the model of GF for LRNS it is expedient to use methods of gradient analysis [14, 15], in order to do which one needs to fulfill the linearization of the navigation function by decomposition in Taylor series by the degrees of amendments δ_j (j=1,2,3,4) with retention of the first members of decomposition:

$$D_i - D_{0i} = \frac{\partial D_i}{\partial x_0}\delta_x + \frac{\partial D_i}{\partial y_0}\delta_y + \frac{\partial D_i}{\partial z_0}\delta_z + \frac{\partial D_i}{\partial w_0}\delta_w,$$
$$i = 1,\ldots,N, \qquad (1)$$

where D_i is the result of the measurement of PR to the i-th PL; D_{0i} is the estimated value of PR to the i-th PL; x_0, y_0, z_0 are the rectangular coordinates of the consumer in geocentric coordinate system (GCS); w_0 is the amendment to the difference in time scales, expressed for clarity in the units of length; N is the number of visible PL, by the signals of which the pseudorange is defined.

Partial derivatives of the system (1) make up the matrix of partial derivatives of the navigation function in the point of location of the consumer with the coordinates (x_0, y_0, z_0), which is the basis for further calculation of assessments of errors in defining the location of the consumer and it is called a gradient matrix:

$$\mathbf{C} = \begin{Vmatrix} \frac{\partial D_1}{\partial x} & \frac{\partial D_1}{\partial y} & \frac{\partial D_1}{\partial z} & \frac{\partial D_1}{\partial w} \\ \dots & \dots & \dots & \dots \\ \frac{\partial D_N}{\partial x} & \frac{\partial D_N}{\partial y} & \frac{\partial D_N}{\partial z} & \frac{\partial D_N}{\partial w} \end{Vmatrix}^{N\times 4}. \quad (2)$$

In our case, differentiation of the function D_i by the variables x, y, z, w produces the following matrix of partial derivatives:

$$C = \begin{Vmatrix} \cos\alpha_1 & \cos\beta_1 & \cos\gamma_1 & 1 \\ \dots & \dots & \dots & \dots \\ \cos\alpha_N & \cos\beta_N & \cos\gamma_N & 1 \end{Vmatrix}^{N\times 4}. \quad (3)$$

The elements of the matrix (3) are the direction cosines of the vectors directed from the consumer to PL in the geocentric coordinate system. If we enter the matrix-column **R** of the differences in the measured and estimated values PR $\mathbf{R} = \left\|D_i - D_{0i}\right\|^{N\times 1} = \left\|r_i\right\|^{N\times 1}$, $i = 1,\dots,N$ and define the amendments $\delta_i\,(i = 1, 2, 3, 4)$ in the form of column matrix $\Delta^T = \|\delta_1 \quad \delta_2 \quad \delta_3 \quad \delta_4\|$, then the system (1) can be written down

$$\mathbf{C}\Delta = \mathbf{R}. \quad (4)$$

To render the system (4) in dimensionless form, both of its parts must be multiplied by the matrix of the weight coefficients:

$$\mathbf{P_0} = \begin{Vmatrix} p_1 & 0 & . & 0 \\ 0 & p_2 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & p_N \end{Vmatrix}^{N\times N}, \quad p_i = \frac{1}{\sigma_{Di}}, \quad (5)$$

where σ_{Di} is the mean-square error of determining PR to the i-th PL.

After this the system (4) will take the form

$$\mathbf{P}_0\mathbf{C}\Delta = \mathbf{P}_0\mathbf{R}. \quad (6)$$

The system (6) is a system of N equations with four unknowns. In general form such system is incompatible and that is why certain combination of four amendments $\delta_i\,(i = 1, 2, 3, 4)$ cannot satisfy this system. Substituting δ_i in the corresponding equation, the left and right parts are not equal and there will be their discrepancy. Applying the procedure of the method of the least squares, minimizing the square of discrepancy of the left and right parts of the system of conditional equations (6), we receive a system of normal equations in the form

$$C^T P_0^T P_0 C\Delta = C^T P_0^T P_0 R. \quad (7)$$

Since $\mathbf{P_0}$ is the diagonal matrix, then its view at transposition does not change, and therefore the product $\mathbf{P_0^T P_0}$ also produces the diagonal matrix **P**, whose elements are the squares of the elements of the matrix $\mathbf{P_0}$. Therefore, we can write

$$C^T P C\Delta = C^T P R. \quad (8)$$

In the system (8) the product $\mathbf{C^T P C = A}$ is the matrix of coefficients of the system of normal equations. The matrix **A** has dimension 4x4, due to the four-dimensional nature of the problem. If the right side (8) $\mathbf{C^T P R}$ is submitted as the corresponding matrix **B**, then the system of normal equations can be written down in the form

$$A\Delta = B. \quad (9)$$

Multiplying the right and left parts of the system (9) by the inverse matrix $\mathbf{A}^{-1}$, one can get solution for the amendments $\Delta = \mathbf{A}^{-1}\mathbf{B}$.

The matrix $\mathbf{P}^{-1}$, which is a part of the matrix $\mathbf{A}^{-1} = \mathbf{C}^{-1}\mathbf{P}^{-1}\left(\mathbf{C}^{-1}\right)^{\mathbf{T}}$, represents variables of the measurements of PR. The matrix $\mathbf{A}^{-1}$ itself has a meaning of correlation matrix of the errors of determining the required settings $\mathbf{K}_q$, on the main diagonal of which are the variables of the parameters that are determined. That is, if we assume the variables of measurements of pseudorange from all PL equal to 1, and the results of the measurements are independent (not correlated) from each other, then on the main diagonal of the matrix $\mathbf{K}_q$ there will be located the coefficients, which are determined only by the geometry of the mutual position of the PL and the consumer. The resulting error of defining the location can be expressed through the trace of the correlation matrix

$$\sigma_q = \left(\mathrm{Tr}\left(\mathbf{K}_q\right)\right)^{\frac{1}{2}}.$$

In general form, the expression for GF can be written down as the ratio

$$\mathrm{GDOP} = \frac{\sigma_q}{\sigma_D},$$

where GDOP is the global dilution of accuracy – common geometric factor, σ_D is the MSE of defining pseudorange to PL; σ_q is the MSE of defining the state vector of the consumer.

For the transition from geocentric to the topocentric coordinate system (TCS) we use afinor transition

$$\mathbf{A}_K = \begin{Vmatrix} \cos\lambda\sin\varphi & \sin\lambda\sin\varphi & -\cos\varphi \\ -\sin\lambda & \cos\lambda & 0 \\ \cos\lambda\cos\varphi & \sin\lambda\cos\varphi & \sin\varphi \end{Vmatrix},$$

where φ and λ are the geodetic coordinates of the consumer.

The correlation matrix $\mathbf{K}_q$ is recalculated to TCS using the formula $\mathbf{K}_{qTCS} = \mathbf{A}_K\mathbf{G}_{KK}\mathbf{A}_K^T$, where $\mathbf{G}_{KK}$ is the unit of the matrix $\mathbf{K}_q$, which corresponds to the errors of coordinates

$$\mathbf{K}_q = \begin{Vmatrix} G_{KK} & G_{Kt} \\ G_{Kt} & G_{tt} \end{Vmatrix}.$$

Thus, the geometric factors of reducing the accuracy in determining the place in space – PDOP, in plan (horizontal plane) – HDOP, by height – VDOP and time – TDOP are written down, respectively:

$$\text{PDOP} = \left(\gamma_{11} + \gamma_{22} + \gamma_{33}\right)^{\frac{1}{2}};$$

$$\text{HDOP} = \left(\gamma_{11} + \gamma_{22}\right)^{\frac{1}{2}};$$

$$\text{VDOP} = \left(\gamma_{33}\right)^{\frac{1}{2}};$$

$$\text{TDOP} = \left(\gamma_{44}\right)^{\frac{1}{2}},$$

where γ_{ij} are the elements of the matrix $\mathbf{K}_q = \mathbf{A}^{-1}$.

In many sources, including [15], it is shown that the minimum values of GF can be achieved when the consumer is in the center of a regular tetrahedron. For a ground consumer, the minimum value is reached when one PL is in the zenith, and the other three are evenly located in the horizontal plane. Thus, to minimize GDOP it is necessary to maximize the volume of the tetrahedron.

5. The model of accuracy of a local radio navigation system considering the instability of functioning of individual elements

So, let there be some space $\mathbf{S}^{\mathbf{F}}$, within the limits of which it is necessary to create a functionally stable radio navigation field **F**. It is necessary to design the structure of the PL network so that at LRNS functioning over a set time **T,** the reliability of navigation of consumers is not below a certain given level, and so that the average accuracy of defining the state vector of the consumer, taking into account a possibility of failure of individual elements of the system through the fault and possible deliberate destruction, stays within the set limits.

In order to formalize the task, the structure of LRNS is advisable to present as an oriented graph $\mathbf{G}^{\mathbf{S}^{\mathbf{F}}} = \mathbf{G}(\mathbf{Z}, \mathbf{U})$ (Fig. 2), where **Z** is the set of vertices of the graph, **U** is the set of arcs of the graph **G**. The vertices of the graph are in three levels (0, 1, 2). Accordingly, the set of vertices **Z** consists of the subsets $\mathbf{Z}_0 \cup \mathbf{Z}_1 \cup \mathbf{Z}_2 = \mathbf{Z}$.

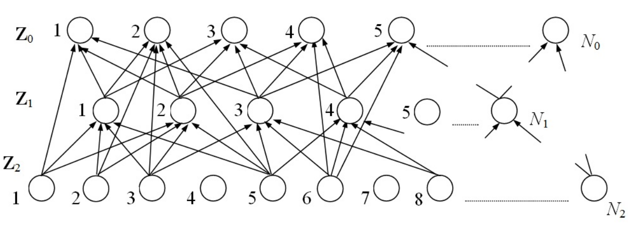

Fig. 2. Structural graph of LRNS

The navigation space $\mathbf{S}^{\mathbf{F}}$ is described by a set of characteristic points of the consumer $\mathbf{Z}_0 = \left\{ \mathbf{z}_{0j} \,\middle|\, j = \overline{1, N_0} \right\}$, which, in turn, consists of the vectors $\mathbf{z}_{0j} = \left(\phi_{0j}, \lambda_{0j}, h_{0j}\right)$, $j = \overline{1, N_0}$, where N_0 is the total number of elements of the set $\mathbf{Z}_0$ – characteristic points of the consumer in the space $\mathbf{S}^{\mathbf{F}}$. Parameters ϕ_{0j}, λ_{0j} are geodetic coordinates of the points $\mathbf{z}_{0j}$, h_{0j} is the height of the point of the consumer over the terrain.

The elements of the set $\mathbf{Z}_1$ are the vectors

$$z_{1j} = \left(\phi_{1j}, \lambda_{1j}, h_{1j}, p_{1j}^{s}\right), \quad j = \overline{1, N_1},$$

where ϕ_{1j}, λ_{1j} are the geodetic coordinates of the points $\mathbf{z}_{1j}$, h_{1j} is the height of APL above sea level, p_{1j}^{s} is the survivability of APL. The value p_{1j}^{s} represents the probability of maintaining the working condition of the complex (Airwehicle+PL) under the influence of destabilizing factors of anthropogenic origin (results of intentional human influence – terrorism) for a specified period of time. The set of anchor points of APL forms the set of vertices of the graph

$$\mathbf{Z}_1 = \left\{ \mathbf{z}_{1j} \,\middle|\, j = \overline{1, N_1} \right\}.$$

All the GPL are described by the set of vectors

$$\mathbf{Z}_2 = \left\{ \mathbf{z}_{2j} \,\middle|\, j = \overline{1, N_2} \right\}$$

with the coordinates

$$z_{2j} = \left(\phi_{2j}, \lambda_{2j}, h_{2j}, p_{2j}^{g}, p_{2j}^{n}, \sigma_{2j}^{\phi}, \sigma_{2j}^{\lambda}, \sigma_{2j}^{h}\right), \quad j = \overline{1, N_2},$$

where ϕ_{2j}, λ_{2j} are the geodetic coordinates of the points $\mathbf{z}_{2j}$, h_{2j} is the height of GPL above the terrain, p_{2j}^{s} is the GPL survivability, p_{2j}^{n} is the reliability of GPS, σ_{2j}^{ϕ}, σ_{2j}^{λ}, σ_{2j}^{h} is the mean-square error (MSE) of GPL attachment to the chosen coordinate system, N_2 is the total number of positions.

The set of arcs **U** of the shown graph $\mathbf{G}(\mathbf{Z}, \mathbf{U})$ consists of information links between the elements of different levels and can be written down as $\mathbf{U} = \left\{ u_{i,j_i}^{k,l_k} \right\}$, where i is the level number, and j_i is the number of the element of the i-th level, from which an arc emanates; k is the level number, and l_k is the number of the element of the k-th level, which includes the arc. The set **U** is described using Boolean variables, for example:

$$u_{i,j_i}^{k,l_k} = \begin{cases} 1, \text{if the condition of} \\ \text{radio visibility is valid;} \\ 0, \text{if the condition of} \\ \text{radio visibility is not valid.} \end{cases}$$

To solve the problem of functional-structural design we introduced the following parametric and functional limitations:

1. The system is considered to be efficient when in sight of each APL there is not less than $m^{\min}$ of GPL, and in the field of view of the consumer there is not less than $m^{\min}$ of pseudolites.

2. The average accuracy of defining the state vector of the i-th consumer σ_i considering stochastic spatial structure of the system should not be worse than a certain value set in advance $\sigma^{\max}: \sigma_i \le \sigma^{\max}$.

3. The probability of successful navigation of the i-th consumer P_i should not be lower than a certain value set in advance $P^{\min}$.

Based on the obtained expressions for geometric factors in general case, the assessment of various variants of setting up LRNS by the accuracy is performed by comparing the values of the variables of an error of determining spatial coordinates based on the ratio $\mathbf{K}_q = \left(\mathbf{C}^{\mathrm{T}} \mathbf{K}_R^{-1} \mathbf{C}\right)^{-1}$ by the formula:

$$\sigma^2 = \gamma_{11} + \gamma_{22} + \gamma_{33}, \tag{10}$$

where γ_{ij} are the elements of the matrix $\mathbf{K}_q$.

The ratio (10) is a criterial function to assess the effectiveness of the structure of LRNS by the accuracy of the system.

For taking into account stochastic nature of existence of individual PL, let us use structural graph $\mathbf{G}(\mathbf{Z},\mathbf{U})$ of the system (Fig. 2). In this graph we will select one point at **0**-level, for example, point 2 (Fig. 3). Consider a model of characteristics of the accuracy and reliability of navigation for the point z_{02}.

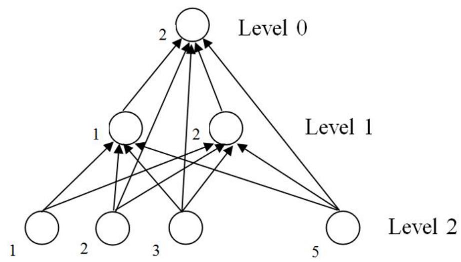

Fig. 3. Element of graph **G(Z, U)**

As we can see, APL z_{11} and z_{12}, as well as GPL z_{21}, z_{22}, z_{23} and z_{25} are in the zone of radio visibility of the point z_{02}. These GPL create a navigation field for APL z_{11} and z_{12}. Thus the parameters of the accuracy of determining the state vector at the point z_{02} will be determined by the accuracy characteristics and relative position of the points z_{11}, z_{12}, z_{22}, z_{23}, z_{25} and by the point z_{02} itself. Considering that each of these points (except for z_{02}) is characterized by its own parameters for survivability and reliability, then by using the previously proposed approach, one can calculate the accuracy of determining the state vector of the consumer given the stochastic nature of the LRNS structure.

To do this, we will further simplify the graph, shown in Fig. 3, leaving only the PL, visible for the point z_{02} and renumber them as shown in Fig. 4. Let us also define (assign) the probability $p_i\,(i=1...5)$ of the existence of each PL.

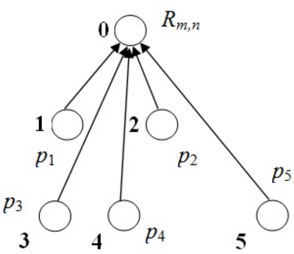

Fig. 4. Elementary graph for the point z_{02}

Navigation problem can be solved only if there are not less than m^{min} functioning PL in the view of the consumer (point **0**). The probability of solving navigation problem at the point **0** can be presented as the probability of events, the essence of which is the simultaneous occurrence of m events out of n possible. Since it is believed that PL operate independently of each other, then the probability of each specific combination of alive/dead PL is defined as the product of the probabilities, in which the letters "p" with different indices enter m times, and the letters q=1–p with different index enter n–m times. In this case, the probability of solving a navigation problem in the point z_{ij} will equal

$$R_{m,n(ij)} = \sum_{r=m}^{n} P_{r,n(ij)}, \tag{11}$$

where

$$P_{m,n(ij)} = \sum_{k} P_{k(ij)}$$

is the probability of simultaneous operation of r PL out of n visible, which is equal to the sum of the corresponding combinations.

Thus in our example:

$$P_{4,5} = q_1p_2p_3p_4p_5 + p_1q_2p_3p_4p_5 +$$
$$+p_1p_2q_3p_4p_5 + p_1p_2p_3q_4p_5 + p_1p_2p_3p_4q_5,$$

$$P_{5,5} = p_1p_2p_3p_4p_5.$$

Let us also remember that each combination has its own value of error variance of determining the state vector of the consumer in the point **0**. By comparing error variance of each combination with its probability, we receive the probability distribution of the accuracy characteristics of the system (Table 1).

Table 1

Accordance of error variance of the combinations to the probabilities of their occurrence

No. of combination	1	2	3	4	5	6	at m<4
σ^2	σ_1^2	σ_2^2	σ_3^2	σ_4^2	σ_5^2	σ_6^2	–
P_k	P_{k1}	P_{k2}	P_{k3}	P_{k4}	P_{k5}	P_{k6}	$1-P_{4,5}$

It is clear from the above-mentioned considerations that the system can enter seven states: 6 functioning combinations and one state when there are not enough visible PL for the navigation determining. Each state is characterized by its own probability of its occurrence P_{ki} and the value of the variance $\sigma_i^2\,(i=1...6)$.

In such case the need to assess the total value of the system σ^2 arises

$$\sigma^2_{ar(ij)} = \sum_{k=1}^{v} \frac{\sigma^2_{k(ij)} P_{k(ij)}}{R_{m,n(ij)}}, \quad v = \sum_{r=m}^{n} C^n_{r\,(ij)}, \tag{12}$$

where the indices indicate: i is the level of LRNS; j is the serial number of the element on the i-th level; k is the number of a combination for the corresponding (ij)-element; m is the number of PL required for determining navigation measuments; n is the total number of visible PL.

5. Discussion of the results of simulation of a spatial structure of a local radio navigation system

In order to analyze the field of accuracy of LRNS, built on the base of basic cell "triangle with a central point", the structure was selected, in which all of the PL are at the height of 8000 m. In this case, the length of the sides of the triangle is 70–80 km. The cell center point is the point with coordinates 49,2° North latitude, 26,5° East longitude (Fig. 5).

The results of performed calculations indicate that the horizontal GF (HDOP) for ground consumers within the working zone does not exceed 20 (Fig. 5, *a*). At the height of 100 m, zone of direct visibility increases to 250 km and so HDOP within the radius of 60–80 km from the center of the cell does not exceed 10, and increases to 200 by the edge of the working area (Fig. 5, *b*).

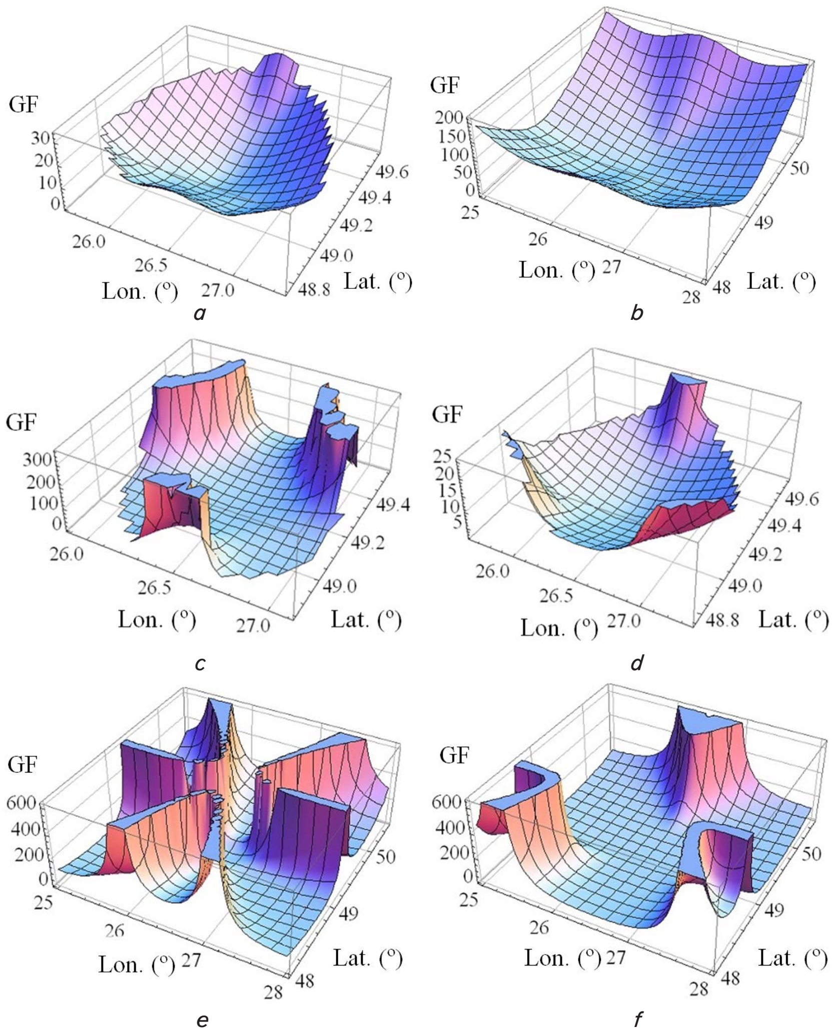

Fig. 5. The field of values of the horizontal geometrical factor HDOP at different heights of the consumer and the geometry of an elementary cell of pseudo satellites: *a* – ground consumer, all PL are at the height of 8 km; *b* – a consumer at the height of 100 m, all PL are at the height of 8 km; *c* – a ground consumer, central PL is at the height of 4 km; *d* – a ground consumer, central PL is at the height of 12 km; *e* – a consumer is at the height of 100 m, central PL is at the height of 4 km; *f* – a consumer is at the height of 100 m, central PL is at the height of 12 km (Lon, Lat are geographical longitude and latitude)

At first glance, central RNT in the elementary cell could be placed slightly lower than the rest of the PL, because the required radius of the performance of this point is less than the rest of the radii. Consider how the field of accuracy changes in this case. For this we place elementary cell, as done previously, as a triangle and calculate the values of GF around it. Fig. 5, *a, b* displays the field of GF with the location of PL at the same height (8 km). Fig. 5, *c* illustrates the field of GF for a ground consumer with decrease in the height of the central PL to 4 km, and Fig. 5, *d* – while increasing the height of the central PL to 12 km. Fig. 5d shows the field of GF to a consumer at the height of 100 m with the height of the central PL of 4 km and Fig 5, *e* – while increasing the height of the central PL to 12 km. As we can see, when changing the height of the central PL, the field of GF is very heterogeneous, due to co-axial location of some PL and the consumers who are positioned on the edge of the zone.

Conducted research into the accuracy of LRNS allows drawing the following conclusions: in designing LRNS, characteristics of its accuracy can be assessed using GF. Receiving spatial values of GF is advisable to carry out with the analysis of gradient fields of navigation parameters. To reduce the error of finding the location it is necessary to increase the gradient of the field of a navigation parameter; for all categories of consumers, the zone of action of the system is limited by the range of direct visibility considering the angle of towering. The most favorable values for horizontal GF (lower than 10) in the system are within the base of the triangle; the characteristic feature of LRNS, in contrast to GNSS, is a significant variability of vertical GF.

However, under conditions of a possible degradation of the structure, the accuracy can dramatically decrease because of unfavorable values of geometric factor. Thus, when designing a structure of the system, the issues of a possible failure (destruction) of the individual elements of the system must be taken into consideration, including, in particular, with the help of the proposed method.

7. Conclusions

1. Introduction of the probability system that describes survivability and reliability of the individual elements to the existing model of the accuracy of pseudolite radio navigation, made it possible to construct a qualitatively new model which takes into account possible course of events under conditions of instability of in the performance of the individual elements of the system, and, therefore, allows tracking the object with greater efficiency.

2. As the components of the vector of the input parameters, the following ones are expedient to choose: parameters of characteristic points of the navigation space, parameters of the anchor points of pseudolites, parameters of the points of a network of infrastructure objects to deploy a network of ground pseudolites, as well as the parameters of the terrain in the defined area.

3. For the synthesis of the systems that operate under difficult conditions of the situation, the most appropriate is the approach based on ensuring sustainability of their operation. In this case, the main criterion for setting up such local radio-navigation systems is the requirement to ensure sufficient accuracy of the navigation of moving objects within a given time with predicted forecast of the possible degradation of a spatial structure.

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