ТЕХНИЧЕСКИЕ НАУКИ

ИНФОРМАТИКА, ВЫЧИСЛИТЕЛЬНАЯ ТЕХНИКА И УПРАВЛЕНИЕ

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АЛГОРИТМ ОПРЕДЕЛЕНИЯ НАЧАЛЬНЫХ КООРДИНАТ РОБОТИЗИРОВАННОГО БЕСПИЛОТНОГО ЛЕТАТЕЛЬНОГО АППАРАТА В УСЛОВИЯХ ИСКАЖЕНИЯ НАВИГАЦИОННОГО ПОЛЯ

ALGORITHM FOR DETERMINING THE INITIAL COORDINATES OF A ROBOTIC UNMANNED AERIAL VEHICLES UNDER NAVIGATION FIELD DISTORTION

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Аннотация. *Роботизированные беспилотные летательные аппараты (РБЛА) широко применяются в военном деле, главным образом в разведке. Крупные аппараты могут быть оснащены вооружением и вести боевые действия.*

Материалы и методы. *Применение РБЛА в гражданских целях также может быть весьма эффективным (мониторинг лесных пожаров, составление топографических карт и т. д.). Большую роль играет метод определения положения и ориентации аппарата в пространстве во время его полета. Чаще всего для этого применяются системы позиционирования GPS/ГЛОНАСС. Однако использование подобных технологий позиционирования может быть затруднено или вообще невозможно. Работа таких систем может быть нарушена в результате целенаправленного подавления либо из-за искажения навигационного поля за счет переотражения навигационного сигнала от искусственных объектов и за счет ограничения видимости горизонта. Сигнал GPS/ГЛОНАСС может оказаться недоступным из-за рельефа горной местности или городских зданий. Использование GPS/ГЛОНАСС может быть неприемлемым по причине секретности или недостаточной точности.*

Результаты и обсуждения. *Поэтому разработка систем позиционирования БПЛА, независимых от данных спутниковых систем навигации, является актуальным направлением исследований. Перспективный способ решения такой задачи – разработка алгоритма определения начальных координат РБЛА в условиях искажения навигационного поля за счет переотражения навигационного сигнала от искусственных объектов и за счет ограничения видимости горизонта. Глобальные навигационные спутниковые системы (ГНСС) являются основным средством навигации для многих подвижных систем и, в частности, для современных роботизированных беспилотных летательных аппаратов. Однако применяемые в навигационных комплексах РБЛА приемники ГНСС обладают крайне низкой помехоустойчивостью, как следствие ограничивают их применение в сложных радиоэлектронных условиях. Практически все виды помех сигналам ГНСС можно разделить на искажения навигационного поля за счет переотражения навигационного сигнала от искусственных объектов и за счет ограничения видимости горизонта. Данные искажения «разрушают» навигационное поле ГНСС. В такой ситуации даже по заранее известны характеристикам каналов навигационных сигналов наблюдается крайне низкий уровень полезного сигнала (минус 161...155 дБВт).*

Заключение. *В статье приведены основные положения математической модели определения точности координат положения объекта со спутников в декартовых координатах. Рассмотрен процесс накопления ошибок позиционирования объекта. Сделаны выводы о параметрах ошибок, влияющих на точность позиционирования объекта, относительно уровня сигнала, принимаемого со спутника.*

Данные исследования выполнены при поддержке научного проекта «Разработка роботизированного беспилотного летательного аппарата мультироторного типа с использованием бесплатформенной инерциальной навигационной системы» Федеральной Целевой Программы на 2014-2020 годы (уникальный идентификатор RFMEFI57818X0222) при финансовой поддержке Министерства Науки и Высшего Образования России, на базе ЦКП СКФУ.

Ключевые слова: матрица положения, матрица точности позиционирования, дисперсия, средняя квадратическая погрешность, GPS, ГЛОНАСС.

Annotation. *Robotic unmanned aerial vehicles (RBLA) are widely used in the military, mainly in intelligence. Large vehicles can be equipped with weapons and conduct combat operations.*

Materials and methods. *The use of RBLA for civilian purposes can also be very effective (monitoring forest fires, drawing up topographic maps, etc.). The method of determining the position and orientation of the device in space during its flight plays an Important role. Most often, GPS/GLONASS positioning systems are used for this purpose. However, using such positioning technologies may be difficult or impossible. The operation of such systems can be disrupted as a result of targeted suppression or due to distortion of the navigation field due to re-reflection of the navigation signal from artificial objects and by limiting the visibility of* *the horizon. The GPS/GLONASS signal may not be available due to mountainous terrain or urban buildings. The use of GPS/GLONASS may not be acceptable due to secrecy or lack of accuracy. Therefore, the development of UAV positioning systems that are independent of satellite navigation systems data is an important research area.*

Results and discussions. *A promising way to solve this problem is to develop an algorithm for determining the initial coordinates of the RBLA in conditions of distortion of the navigation field due to re-reflection of the navigation signal from artificial objects and by limiting the visibility of the horizon. Global navigation satellite systems (GNSS) are the main means of navigation for many mobile systems and, in particular, for modern robotic unmanned aerial vehicles. However, GNSS receivers used in rbla navigation systems have extremely low noise immunity, which consequently limits their use in complex radio-electronic conditions. Almost all types of interference to GNSS signals can be divided into distortions of the navigation field due to re-reflection of the navigation signal from artificial objects and by limiting the visibility of the horizon. These distortions "destroy" the GNSS navigation field. In this situation, even if the characteristics of the navigation signal channels are known in advance, there is an extremely low level of the useful signal (minus 161...155 dBW).*

Conclusion. *The article presents the main provisions of the mathematical model for determining the accuracy of the coordinates of the object's position from satellites in Cartesian coordinates. The process of accumulating object positioning errors is considered. Conclusions are made about error parameters that affect the accuracy of object positioning, relative to the signal level received from the satellite.*

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Key words: position matrix, positioning accuracy matrix, variance, mean square error, GPS, GLONASS.

Introduction. When determining the position of an object in Cartesian coordinates, special signals are used. Each GPS satellite constantly transmits navigation messages containing, in particular, the coordinates of the satellite at the time of sending the message and the time of sending. A GNSS receiver receiving such a message from a satellite navigation system (SNS) can calculate the distance to the satellite:

$$d = (t^{(\text{пр})} - t^{(\text{отпр})}) \cdot \text{c}. \tag{1}$$

In this formula, the transit time of the signal (from the time of sending $t^{(\text{отпр})}$ to the time of receiving $t^{(\text{пр})}$) multiplied by the speed of propagation of the radio signal, i.e. the speed of light c.

The geometric interpretation of the system for determining the position of an object in Cartesian coordinates is as follows. A message in the form of a signal area from one satellite selects a part of the space in which the consumer is located - a sphere determined by its center-satellite and radius. The information from the second satellite is another sphere of the signal space. The message from the third satellite adds more parameters of the signal space and uniquely determines the coordinates using the method of comparison. The condition that all three spheres have a common point follows from the design of the navigation system itself. Of the two solutions (intersections of the circle and the third sphere), one is implausible, and the second contains the true coordinates of the object's position in Cartesian coordinates.

Thus, the problem of determining the initial coordinates of an UAV under conditions of distortion of the navigation field due to re-reflection of a signal from artificial objects and by limiting the visibility of the horizon is relevant and significantly affects the efficiency of processing GPS / GLONASS data and the accuracy of determining the location of objects (for example, unmanned aerial vehicles).

It is necessary to develop a methodology that allows determining the initial location of the SSV, assessing the quality of the navigation signal, for making a decision on entering the initial coordinates into the inertial navigation system (SINS) in conditions of shading and receiving the reflected signal from the SNS.

Materials and methods. In [1–4], methods are given that allow determining the initial location of an SSV, but do not explain the effect of satellite geometry on the accuracy of object positioning.

Figure 1 shows the distances R_i ($i = 1 \ldots 4$) from satellites to the user.

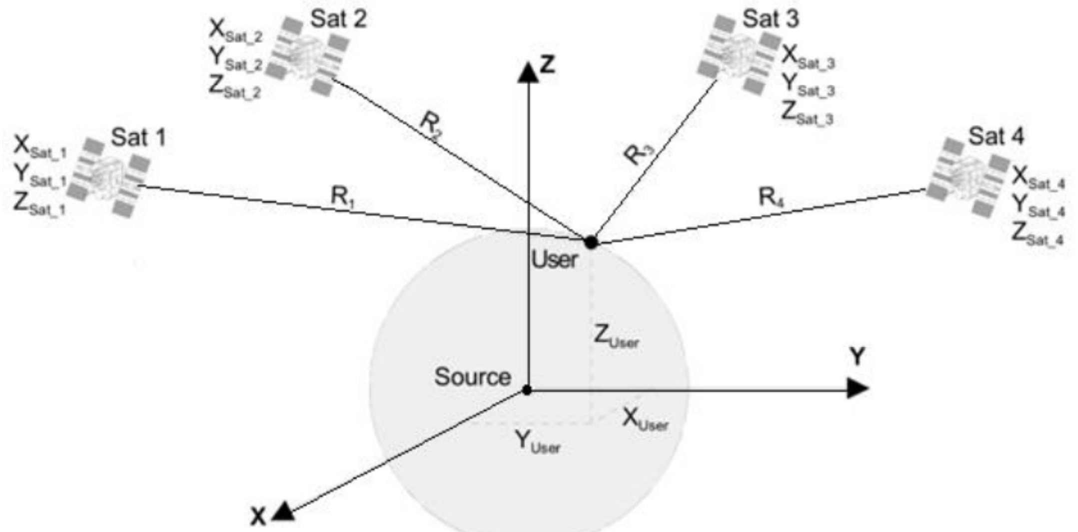

Fig. 1. Description of the satellite and the position of the UAV in Cartesian coordinates

Distances R_i (i can be determined using the formula:

$$R_i = \sqrt{(X_{Sat\_i} - X_{User})^2 + (Y_{Sat\_i} - Y_{User})^2 + (Z_{Sat\_i} - Z_{User})^2}\,. \tag{2}$$

Using the coordinates shown in Figure 1, we obtain the position matrix P [] of the object in Cartesian coordinates:

$$P = \begin{bmatrix} \dfrac{X_{User} - X_{Sat\_1}}{R_1} & \dfrac{Y_{User} - Y_{Sat\_1}}{R_1} & \dfrac{Z_{User} - Z_{Sat\_1}}{R_1} & 1 \\ \dfrac{X_{User} - X_{Sat\_2}}{R_2} & \dfrac{Y_{User} - Y_{Sat\_2}}{R_2} & \dfrac{Z_{User} - Z_{Sat\_2}}{R_2} & 1 \\ \dfrac{X_{User} - X_{Sat\_3}}{R_3} & \dfrac{Y_{User} - Y_{Sat\_3}}{R_3} & \dfrac{Z_{User} - Z_{Sat\_3}}{R_3} & 1 \\ \dfrac{X_{User} - X_{Sat\_4}}{R_4} & \dfrac{Y_{User} - Y_{Sat\_4}}{R_4} & \dfrac{Z_{User} - Z_{Sat\_4}}{R_4} & 1 \end{bmatrix}. \tag{3}$$

Required:

1. Determine the indicators describing the influence of satellite geometry on the positioning accuracy of the object Ri.
2. To develop a methodology for determining the initial coordinates of an UAV in conditions of distortion of the navigation field due to re-reflection of the navigation signal from artificial objects and due to limiting the visibility of the horizon.

Results and discussion. Applying sequentially the transposition of the position matrix, multiplication and inversion, we calculate the inverse matrix DOP D [1], designed to determine the influence of satellite geometry on the positioning accuracy of an object:

$$D = \left[[P]^T \bullet [P]\right]^{-1}. \tag{4}$$

Using the matrix calculation rules, the 16 elements of the DOP D matrix are denoted as follows:

$$D = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{bmatrix}. \tag{5}$$

The following DOP indicators are known that describe the effect of satellite geometry on the positioning accuracy of an object [1, 3]:

– GDOP (Geometric DOP): describes the effect of satellite geometry on positions in 3D space and time;

– PDOP (Positional DOP): describes the effect of satellite geometry on positions in 3D space;

– HDOP (horizontal DOP): describes the effect of satellite geometry on position in plane (2D);

– VDOP (Vertical DOP): describes the effect of satellite geometry on altitude (1D);

– TDOP (Time DOP): describes the effect of satellite geometry on time measurement.

The general error in the position of the UAV is determined by the accumulation of errors of the factors considered above, and they, in turn, can be calculated from the elements of the matrix DOP D as follows:

$$GDOP = \sqrt{D_{11} + D_{22} + D_{33} + D_{44}}\,. \tag{6}$$

$$PDOP = \sqrt{D_{11} + D_{22} + D_{33}}\,. \tag{7}$$

$$HDOP = \sqrt{D_{11} + D_{22}}\,. \tag{8}$$

$$VDOP = \sqrt{D_{33}}\,. \tag{9}$$

$$TDOP = \sqrt{D_{44}}\,. \tag{10}$$

Therefore, in the case when the elements of the DOP matrix D (5) are known, it is possible to determine the DOP indicators describing the effect of satellite geometry on the object positioning accuracy R_i. These parameters are functions of the corresponding covariance matrices of elements in the global or local geodetic coordinate system. They can be obtained mathematically from the position of the available satellites (navigation signal sources). Many GNSS receivers allow you to display the current location of all satellites (“satellite constellation”) along with DOP values.

The method for determining the initial coordinates of an SSV in conditions of distortion of the navigation field due to re-reflection of the navigation signal from artificial objects and due to limiting the visibility of the horizon is as follows:

1. Based on the received signals, it is necessary to compose a matrix of positions P [] of the object in Cartesian coordinates (formula (3)).

2. Calculate the matrix of the influence of satellite geometry on the positioning accuracy of the DOT object according to the formula (5).

3. Determine the DOP indicators according to formulas (6) - (10).

4. Check the accuracy of the assessment of the initial coordinates of the ballistic missile system according to the ratios:

$$PDOP^2 = HDOP^2 + VDOP^2 \text{ и } GDOP^2 = PDOP^2 + TDOP^2\,. \tag{11}$$

The source [1] shows that the accuracy of measuring the location of an object is proportional to the DOP values. This means that when the DOP value is doubled, the object location error also doubles. The following relationships apply:

- error $R_i\,(1\sigma)$ = 1* Total RMS * value DOP;
- error $R_i\,(2\sigma)$ = 2* Total RMS * value DOP;
- RMS (Root Mean Square) - root mean square error.

Table 1 shows the types of horizontal errors depending on the mean square error (1σ = 68 %, 2σ = 95 %) with HDOP = 1.3.

Long-term measurements, available from the US FAA, showed that 95% of all measurements had horizontal and vertical errors less than 7.4 and 9.0 m, respectively. The time period for the measurement was 24 hours [1].

In the source [1], the DOP value is defined as the reciprocal of the volume of the tetrahedron, composed of the position of the satellites and the user (Figure 2, volume indicator).

When modeling various situations and drawing up a methodology, the following conclusion was made: the larger the internal volume of the tetrahedron, the lower the DOP value.

Table 1

Types of horizontal errors with HDOP = 1.3

Error type	Error
Total RMS	4 м
Horizontal error Ri (1σ = 68%, HDOP = 1.3)	6 м
Horizontal error Ri (2σ = 95%, HDOP = 1.3)	12 м

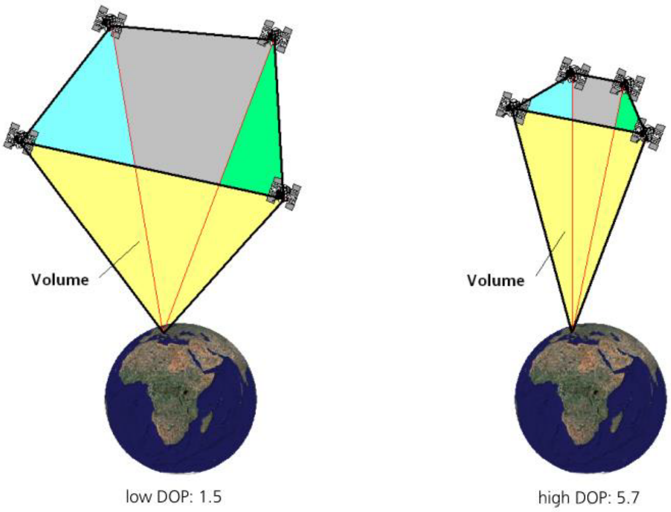

Fig. 2. Influence of satellite geometry on the positioning accuracy of the object (RBV)

Studies have shown that with open and free areas (no shading), the satellite communication area is favorable for DOP values, and they rarely exceed 3 (Figure 3).

In mountainous areas, forests and urban areas, the DOP values, in contrast to the cases discussed above, have values much greater than one, which makes it difficult to determine the position of an object in space.

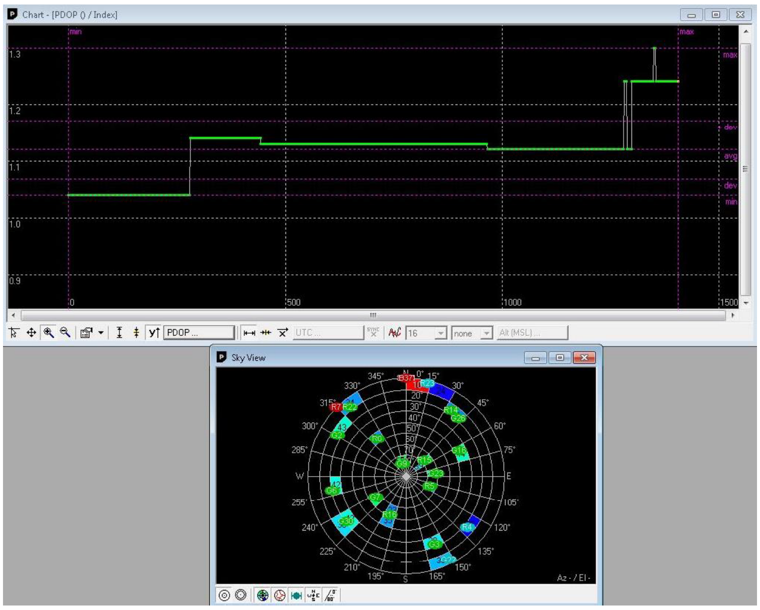

Fig. 3. HDOP values, in the area without shadow / obstruction of the satellites (maximum PDOP value <1.4)

Figures 3 and 4 show the cases of PDOP change in the absence (maximum PDOP less than 1.9) and presence of obstructions (maximum PDOP greater than 20) satellite visibility, respectively. In the experiment for Figure 4, the western area is shaded by a tall building.

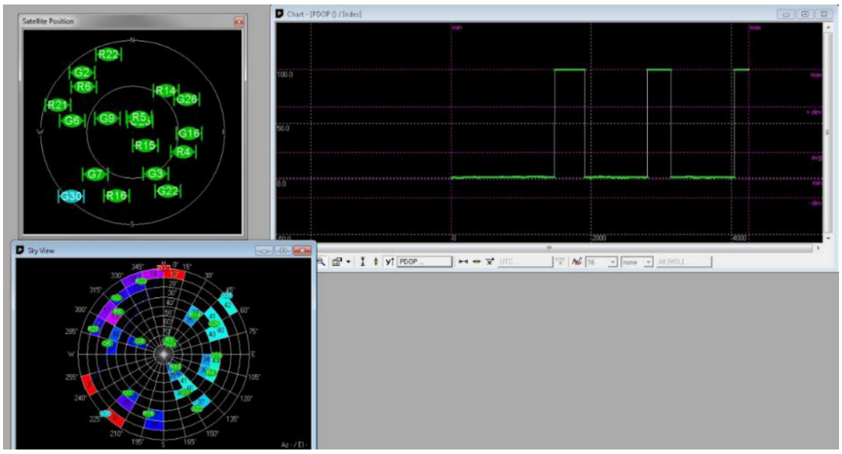

Fig. 4. PDOP values, high shadow / obstruction of satellites (maximum PDOP> 20)

In the case of strong shading (Figure 4), the temporary ability to determine the position of the object with the required accuracy (DOP <2) is rather small and has a random nature.

For accurate measurements, it is recommended in [4] that time periods with DOP values above 6 should not be used for accurate measurements.

DOP values can be estimated based on the current position of the constellation of satellites [2, 3].

During the experiment, the calculated DOP values coincided with the measured ones, which confirms the correctness of the developed technique. In order to actualize the determination of the initial coordinates of the UAV experimentally in conditions of distortion of the navigation field due to re-reflection of the navigation signal from artificial objects and with limited visibility of the horizon, studies were carried out when the location of navigation satellites is shown in Figure 5, where the western side is shaded.

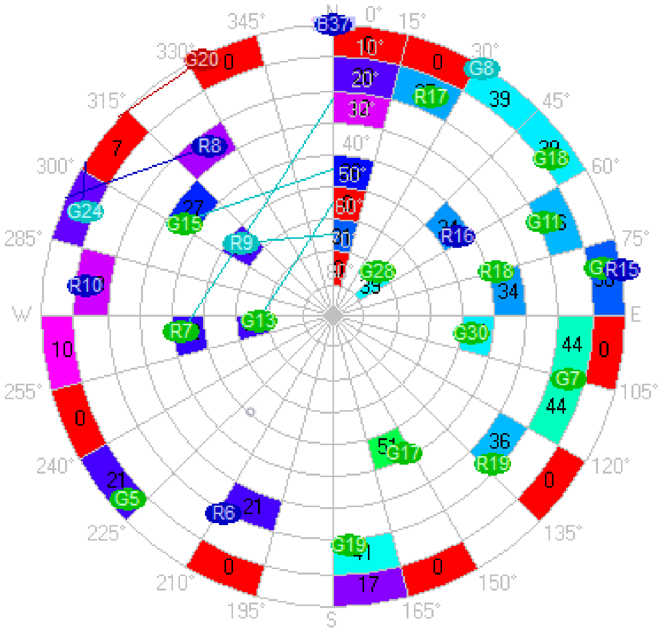

Fig. 5. Location of navigation satellites during the experiment

The figure shows that satellites G15, G13, G5 and R7 are out of line of sight of the antenna of the navigation receiver, nevertheless, the data from these satellites take part in the formation of the navigation solution. Their signals are reflected from the metal roof of a nearby building, thereby introducing an error in determining the coordinates of the location.

The received signal is characterized by a step change in level from 20 to 33 dbHz. The satellites listed above are periodically automatically excluded by the GNSS receiver from the navigation solution.

For comparison, the signal strength of the G17 satellites is 43-50 dbHz,

G1 44–46 dbHz, which are in line of sight.

In the course of the experiment, it was determined that another characteristic sign of the reception of the reflected signal is an abrupt change in the estimate of the decrease in the accuracy of the received GDOP signal from 1.45 to 2.9, which can be observed in the interval in 10-12 minutes.

Under normal conditions, the GDOP parameter changes slowly, the rate of its change is commensurate with the time of change of visible satellites above the horizon.

Based on the analysis and experiment performed, it is possible to conclude that an increase in HDOP of more than 2 is a necessary, but not sufficient condition for the distortion of the navigation field. The analysis should also include the received signal strength of a particular satellite, as well as the rate of change of the GDOP parameter.

Thus, it is necessary to determine the initial position of the UAV, assess the quality of the navigation signal, make a decision on the algorithm for the correction of the onboard SINS during takeoff and landing in conditions of shading and the possible reception of the reflected signal from the SNS.

Possible conditions are:

1. The received signal can be used to initialize the SINS and determine the position of the UAV with high accuracy.
2. It is possible to determine the location of the UAV with reduced accuracy.
3. It is possible to determine the position of the UAV with a large error.

An analysis of a full-scale experiment showed that in order to achieve the maximum accuracy in determining coordinates during the preparation of an UAV for takeoff, it is recommended to carry out a tolerance control of the dispersion of the carrier-to-noise ratio of the navigation radio signal received from the satellites by the GNSS receiver.

If there are at least 7 satellites with normal dispersion indices, and when the HDOP, GDOP parameters are in tolerance, it is necessary to record the navigation parameters into an array containing the fields: longitude, latitude, altitude, HDOP parameter, GDOP parameter. This array will contain navigation parameters with the best indicators of the accuracy of determining the coordinates of the aircraft.

If the HDOP or GDOP indicators do not meet the specified requirements, but the received navigation radio signal from at least 7 satellites meets the requirements for the carrier-to-noise ratio, in this case the navigation parameters recorded in the array will meet the reduced requirements for position determination accuracy UAV.

In the presence of a navigation radio signal satisfying a given carrier-to-noise ratio from less than 7 satellites, the navigation data recorded in the array will determine the position with a low accuracy in determining the position of the ballistic missile. In this case, the following solutions to this problem are possible:

1. Change the launch site of the UAV.
2. Carry out the determination of the initial coordinates using other methods, for example, electronic maps using known landmarks on the ground. Further, it is necessary to load the obtained coordinates into SINS. In this case, it is necessary to estimate the vertical take-off altitude of the SSV in order to leave the zone of the distorted navigation field. During takeoff, the SINS correction from the SNS receiver should not be performed.

In the SNS receiver [4,5], it is possible to use models for calculating navigation parameters depending on the dynamics of objects.

When working with loads <1 g, the model for calculating coordinates assumes a highly dynamic object that can change its speed with an acceleration of up to 1 g, as a result of this the spread of coordinates given by the receiver at rest will be large. When switching to a stationary dynamic platform model, the variance of the generated coordinates will be small.

The dynamic model "Aviation <1 g" is working for UAV. The use of the "stationary" dynamic platform model in determining the coordinates of the initial position will significantly reduce the variance of the initial position coordinates obtained from the SNS receiver.

The operation of the algorithm involves several stages:

1. The stage of configuration of the SNS receiver to work with the model of a stationary object. At this stage, the dynamic model is switched, which is used to estimate the coordinates of the location and check the correctness of the switch.
2. Stage of assessment of the received parameters. The variance is assessed:
   – CNO ratio – carrier / noise, for the navigation signal received from satellites;
   – HDOP – factor of decrease in the accuracy of determining coordinates in the horizontal plane;
   – GDOP – geometrical factor of decrease in coordinate determination accuracy.
3. The stage of dividing the received coordinates depending on the characteristics of HDOP, GDOP and CNO, and writing data to arrays.
4. The stage of determining the accuracy of the navigation data provided for the SINS initialization. At this stage:
   – a decision is made on the availability of UAV position data;
   – depending on the parameters of the received signals, the accuracy factor of the navigation solution is established;
   – a data readiness signal is generated for SINS initialization;
   – if it is impossible to determine the coordinates with a given accuracy, a message is issued to the operator to make a decision about another method of initial SINS initialization.
5. The stage of switching the used dynamic platform to "Aviation <1 g" and checking the correct switching.

Conclusions. In this paper, we propose a method for determining the initial coordinates of an SSV under conditions of distortion of the navigation field due to re-reflection of the signal from artificial objects and due to limiting the visibility of the horizon.

The technique, presented in the form of a sequence of actions and equations (5–11), makes it possible to determine the initial location of the ballistic missile system, to assess the quality of the navigation signal, to make a decision on entering the initial coordinates into the SINS under shading conditions and receiving the reflected signal from the SNS. It is based on the use of the HDOP and GDOP parameters, which make it possible to form the initial navigation parameters for loading into the SINS with the best indicators in determining the accuracy of the coordinates of the SSV, in the presence of at least 7 satellites with normal carrier-to-noise ratio.

A feature of this technique is that an onboard GNSS receiver is used as a meter for HDOP and GDOP parameters.

On the basis of the technique, an algorithm has been developed for estimating the parameters of the received navigation signal, which makes it possible to identify the fact of distortion of the navigation field, to minimize the errors that arise when determining the initial coordinates of the ballistic missile.

The estimation of the accuracy of determining the coordinates of a location has three states. The coordinates of the initial location determined by the algorithm can be used to initialize the SINS:

– with high precision;
– with reduced accuracy;
– with a large margin of error.

In the latter case, it is necessary to change the place of the planned take-off of the RBVA. Or estimate the altitude at which the conditions of distortion of the navigation field will be eliminated due to re-reflection of signals or shading of the line of sight of the satellite. After initialization with parameters of low accuracy, take off in the SINS autonomous mode. Turn on the correction after leaving the area of distortion of the navigation field.

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