AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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AIRCRAFT NAVIGATION EFFICIENCY IMPROVING DURING LANDING USING SATELLITE NAVIGATION SYSTEM

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Abstract

Purpose: *Two algorithms have been considered in this article. Both of them make possible to improve aircraft navigation efficiency during landing by satellite navigation system signals. The first algorithm describes creation of two reference planes in space using measured coordinates of four points on the runway and the subsequent calculation of the aircraft horizontal and vertical angular deviation from these planes. The second algorithm describes an autonomous integrity control in the aerodrome area when four satellites are visible.* ***Methods:*** *methods of experiment planning, analytic geometry and linear algebra have been used.* ***Results:*** *obtained a new experimental data.* ***Discussion:*** *The results of experimental research of the first algorithm showed the principal possibility of deviation calculation in this way. It is shown that implementation of this technology will make it possible to increase the efficiency of small aircrafts navigation during landing at aerodromes and landing areas that are currently not equipped with radio equipment for instrument landing. The results of research of the second algorithm showed that it allows reducing the number of satellite navigation system failures and also enhances navigation efficiency. These results can be used in the aerospace sector for reducing the number of small aircraft non-flying periods.*

Keywords: aircraft landing; global navigation satellite system; instrument landing; integrity; navigation efficiency; precise landing.

1. Introduction

Small aircraft is in demand in many branches of the national economy - forestry, agriculture, firefighting, etc. The leading role is played by small aviation in the training of flight crew members. Low requirements to the quality and geometric dimensions of the runway allow small aircraft to have a wide geography of flights and to carry out promptly. But since flights are performed mainly on unequipped airfields, this imposes significant restrictions during landing.

Landing of the aircraft is a decrease along a rectilinear trajectory inclined to the horizon at an angle of 2.5-3.5 ° (for mountain airodromes this value can reach 5 °). Currently, at most classified and unclassified aerodromes for small aircrafts the visual landing is usually performed. This, along with the implementation of VFR (visual flight rules) flights, avoids unnecessary costs for aerodrome radio equipment, certification of the air fleet for instrumental flights and air navigation services. However, VFR flight and visual landing have significant restrictions on meteorological conditions, which lead to frequent downtimes. The equipment of airfields and landing areas with means ensuring vertical and horizontal guidance of aircraft would significantly reduce the number of non-flying weather conditions and increase the efficiency of the use of the air fleet. Obviously, the use of the radio-navaid system like Instrument Landing System (ILS) for this purpose is inadvisable due to the high cost of its installation (at least $ 800,000) and maintenance (about 10% of the installation cost annually), as well as the long duration of the deployment process. The problem can be solved by guiding the aircraft by the signals of satellite navigation systems.

2. Analysis of latest research and publications

The Global navigation satellite system (GNSS) technologies are being rapidly introduced in all industries where the time and coordinates detection is needed. The European Agency for GNSS periodically publishes detailed reports about the development, production, use of satellite navigation devices and the elemental base for their creation. A fragment from one of these reports [1] is shown in Fig. 1. It concerns the distribution of services between different categories of GNSS users.

GNSS technologies are practically not applied in Ukrainian aviation despite their proved economic and technical attractiveness. One of the reasons is the lack of a regulatory framework. Some economic and technical aspects of the effectiveness of GNSS technologies for navigation in Ukrainian aviation were considered in [2 - 5].

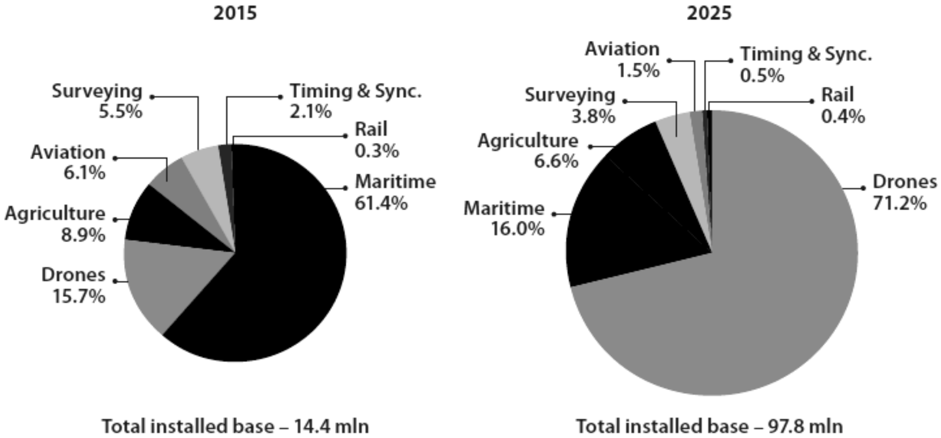


Fig. 1. Distribution of services between different categories of GNSS users.

The GNSS Guide [6] emphasizes that states implementing satellite navigation technologies in aviation take responsibility for safety at all stages of the flight and provide supervision and control of satellite signals in space. The wide-scale implementation of GNSS should be preceded by the development of the operational concept (CONOPS) and a detailed business case that takes into account interests of all stakeholders. In particular, the advantages, costs and benefits of using space and terrestrial functional additions (SBAS and GBAS), dependent surveillance systems (ADS-B/C). The document [7] outlines some of Ukraine's intentions to implement GNSS technologies. However, they have a very general nature and outline only strategic goals.

3. Research tasks

The research task is to develop ways of increasing aircraft navigation efficiency during landing using satellite system signals. For this purpose, it is necessary to develop an aircraft guidance technique during landing and an algorithm for ensuring the navigation field integrity.

4. The solution of the problem

To provide aircraft guidance, the coordinates of some points on the runway have to be measured and a block of relevant data has to be transmitted to the aircraft, allowing the formation of reference surfaces and calculating the deviations of the aircraft from these surfaces. The data block can also be pre-entered into the on-board computer database. One of the algorithms for deviations calculating is considered in [8]. To determine the spatial position of the runway and reference planes, it is necessary to measure the three-dimensional coordinates of four points on the runway (Fig. 2).

The point L is set at the intersection of the central axis of the runway and its landing threshold. The point T is set directly above the point L at the desired height of the aircraft flying above the threshold of the runway. Point P (the point at which the glide path is projected) is selected on the central axis of the runway in such a way that allows to set the glide path slope angle within acceptable limits. The point K is selected at the edge of the runway in such a way that the segment PK is perpendicular to the axis of the runway and parallel to its ends. In contrast to the methods for aircraft deviations calculating presented earlier by Rockwell Collins [9] and The Boeing Company [10], the presented method allows defining the reference surfaces in space as intersecting planes, which greatly simplifies calculations.

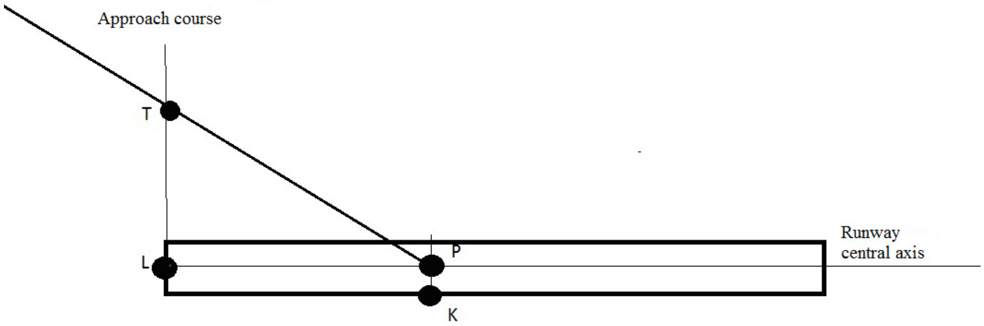


Fig. 2. Illustration of the selection of 4 points on the runway

The equation of a plane in space can be defined as follows [11]:

$$\begin{vmatrix} x-x_1 & y-y_1 & z-z_1 \\ x_2-x_1 & y_2-y_1 & z_2-z_1 \\ x_3-x_1 & y_3-y_1 & z_3-z_1 \end{vmatrix} = 0 \qquad (1)$$

In the equation (1) $(x_1\ y_1\ z_1)$, $(x_2\ y_2\ z_2)$, $(x_3\ y_3\ z_3)$ are the coordinates of points which are not lying on the same line. The determinant of the third order of the square matrix is found according to the rule of Sarrus.

As a result, we obtain the equation of the plane in the form $Ax + By + Cz + D = 0$. The course plane is given by the coordinates of the points T, L, P, the plane of the glide path is given by coordinates of the points K, P, T. The on-board GNSS receiver measures its own coordinates (x, y, z) and substitutes them into the plane equations. If the result of the coordinates substitution in the course plane equation becomes a positive value, then the aircraft is to the right of the reference trajectory. The negative value means that aircraft is to the left of the course plane. For the glide path plane, a positive value corresponds to an upward deflection, a negative value corresponds to a downward deflection. The quantitative measurement of the linear deviation can be performed using the equation (2):

$$d = \frac{|A \cdot x + B \cdot y + C \cdot z + D|}{\sqrt{A^2 + B^2 + C^2}} \qquad (2)$$

The angular deviation of the aircraft can be calculated using the equation:

$$\sin\alpha = \frac{|A \times l + B \times m + C \times n|}{\sqrt{A^2 + B^2 + C^2} \times \sqrt{l^2 + m^2 + n^2}} \qquad (3)$$

In the equation (3) A, B, C are the coefficients of the equation of the plane, l, m, n are the coefficients of the directing vector of the line which connects points M and P (the center of mass of the aircraft and the point at which the glide path is projected).

The next stage is ensuring required navigation performance. Navigating by satellite navigation systems requires continuous monitoring of the operational characteristics of the signal in space. Monitoring is subject to such parameters as:

- accuracy - the difference between calculated and true position of the aircraft;
- integrity - the probabilistic measure of trust in the correctness of information issued by the entire system. Integrity provides the ability of the system to alert the user that it should not be used for the intended flight operation. The integrity of GNSS is determined by on-board equipment through performing complex computing operations. The system has integrity if the error in the calculated location does not exceed the maximum allowed value for the operation being performed;
- continuity of service - the ability of the system to function without unplanned interruptions during the flight operation;
- availability of service - the period of time during which the system simultaneously provides required accuracy and integrity.

Table 1 shows some requirements for the accuracy, integrity, availability of service of the satellite radio navigation system for various landing categories in accordance with [12].

The integrity of satellite navigation systems is usually controlled by the GNSS control segment. However, it may take several minutes before the control segment detects a satellite’s pseudorange measurement error and excludes the faulty satellite from the navigation solution. This time period which is uncritical for most GNSS users may be critical for aircraft during the landing phase. Therefore GNSS navigation is not possible without integrity control performed directly in the on-board receiver (RAIM) or in the on-board computer using aid of other navigation devices (AAIM). For RAIM algorithms that are currently in use redundant measurements are required, i.e., at least 5 navigation satellites of one system should be visible to the on-board receiver if GNSS is used as a subsidiary navigation aid and at least 6 if GNSS is used in as the main navigation aid [13]. There are usually from 8 to 11 satellites in a well-viewed area. To determine the coordinates in 4D with one system, 4 satellites are sufficient. When small aircraft performs landing on an unequipped landing field, it is possible to reduce the number of visible navigation satellites to 4 due to terrain features or radio interference. The group of 4 satellites ensures location (according to [14], in 12% of cases dilution of precision (DOP) will have an acceptable value for landing), but standard RAIM algorithm will detect a non-alternative failure. Since landing is usually conducted in the local area, integrity can be controlled by the ground receiver. This will also make it possible to predict in advance which subcombinations of 4 satellites from the entire visible set of satellites will provide acceptable navigation accuracy. Information about all possible subcombinations and the geometric factor provided by each of them can be broadcasted using the radio data channel or pre-entered into the onboard computer.

Table 1

Requirements for the accuracy, integrity, availability of service of the satellite radio navigation system for various landing categories

Phase of flight	Accuracy (95% error)	Integrity		Alert Limit (H: horizontal, V: vertical	Continuity	Availability
		Time to Alert	Pr (HMI)			
LPV (APV 1.5)	H: 16 m V: 20 m	10 sec	$2*10^{-7}$/ approach	H: 40 m V: 50 m	$5{,}5*10^{-5}$/ approach	0.99 to 0.99999
APV-2	H: 16 m V: 7,6 m	6 sec	$2*10^{-7}$/ approach	H: 40 m V: 20 m	$5{,}5*10^{-5}$/ approach	0.99 to 0.99999
CAT I	H: 16 m V: 4 to 7,6 m	6 sec	$2*10^{-7}$/ approach	H: 40 m V: 10 to 12 m	$5{,}5*10^{-5}$/ approach	0.99 to 0.99999
CAT II	H: 6,9 m V: 2.0 m	2 sec	$2*10^{-9}$/ approach	H: 17,4 m V: 5,3 m	$4*10^{-6}$/ approach	0.99 to 0.99999
CAT III	H: 6.1 m V: 2.0 m	1 to 2 sec	$2*10^{-9}$/ approach	H: 15,5 m V: 5,3 m	H: $2*10^{-6}$/ 30 sec V: $2*10^{-6}$/ 15 sec	0.99 to 0.99999

The proposed integrity check algorithm, like the standard RAIM algorithms, consists of two stages. At the first stage the geometric factor of the visible satellites is determined. If the DOP value is unsatisfactory, computer doesn't perform further calculations and declares integrity failure. If DOP value is satisfactory, computer determines the test statistics.

In a second step computer calculates a pseudo-range discrepancy for each of the visible satellites, - the difference between the measured pseudo-range and the pseudo-range value which was predicted from the base receiver location data and ephemeris data.

According to [15], the connection between the discrepancies of pseudoranges to satellites and the error in users location determining is described by the equation:

$$\sigma_i = \sigma_0 \times DOP \quad (4)$$

In the equation (4) σ_i is the standard error characterizing the accuracy of plan coordinates, height or time measuring, σ_0 is the standard unit weight error characterizing the accuracy of the pseudo-range (or phase) measurement.

If computer detects a satellite whose pseudo-range error exceeds the threshold calculated for a particular DOP value, it excludes such a satellite from the navigation decision. Since the elimination of the satellite entails a change in the geometric factor, computer calculates a new threshold for the new DOP value. The cycle is repeated until the value of the discrepancy (residual) for each of the satellites involved in solving the navigation task is less than the threshold, or until the number of satellites becomes less than 4 (in the latter case, a satellite navigation failure is declared). The scheme of the algorithm is shown in Fig. 3.

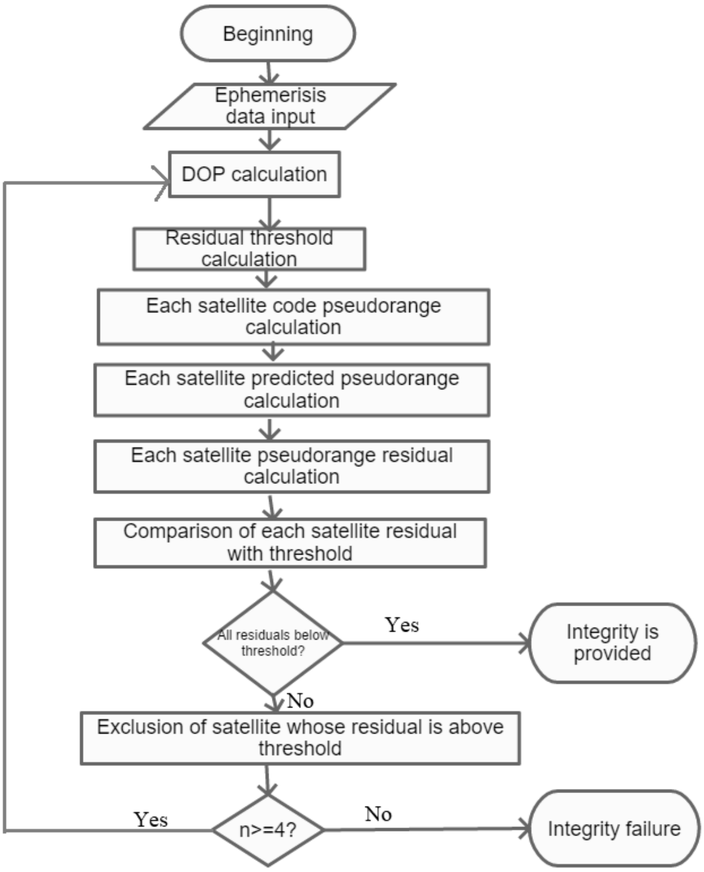
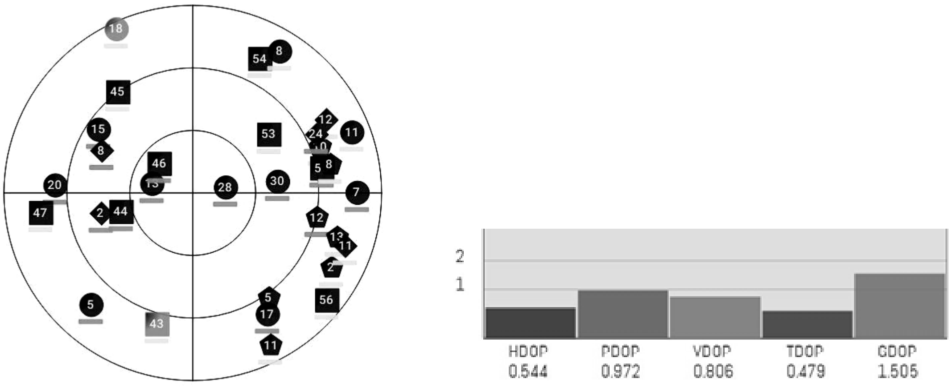


Fig. 3. The scheme of the integrity check algorithm

If flight management computer uses navigation equipment in which combined signals from GPS, GLONASS, GALILEO, COMPASS are processed, the task of integrity control can be solved according to the scheme described above, taking into account that the minimum number of satellites for coordinates measurement is:

$$Min = N + 3 \qquad (5)$$

In the equation (5) N is the number of satellite systems being in use. Fig. 4 shows the instantaneous visibility of the satellites of the four systems.



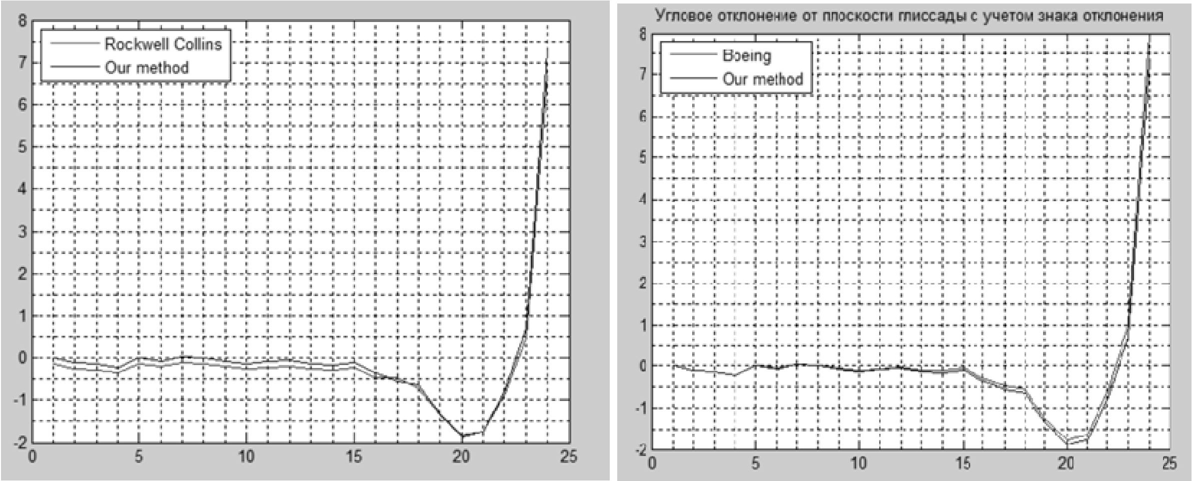
a *b*

Fig. 4. Visibility of the satellites: *a* – Instantaneous visibility of the satellites of the four systems; *b* – Geometric factors of visible satellites

In Fig. 4 there are 32 GPS, GLONASS, GALILEO and COMPASS satellites. Satellites 18 (GPS) and 43 (GLONASS) are not operable and they are excluded from the calculations. If we assume that during landing some of the satellites will be blocked, we can create a database of all combinations which contain 4 satellites out of visible 30, calculate geometric factors and select those combinations of satellites that provide the required accuracy and integrity (as a selection criteria we can take the value of DOP close to the values shown in Figure 4, b). Note also that the database can be expanded by using only two (three) systems. This approach to integrity control allows significant increasing the efficiency of evaluating the accuracy of determining the coordinates of integrity.

5. Results and discussion

An experimental study of the considered guidance algorithm showed insignificant discrepancies between the deviations obtained and the results of deviations calculating using the methods considered in [9-10] (Fig. 5).



a *b*

Fig. 5 The result of comparison of the obtained aircraft deviations from the reference surfaces with deviations obtained by: *a* - the Rockwell Collins method; *b* - the Boeing Company method

These results show principal possibility of considered technique implementation. But what is the impact of satellite landing system on the navigation efficiency?

The assessment of airline activities from an economic point of view is usually being performed according to the following criteria. One of the main indicators for firefighting, sanitation, ice reconnaissance, air defense and other industries, according to [16], is the total adjusted number of flying hours which is calculated by the equation:

$$W_{fh}^{adj} = \sum W_{fh}^{ij} \times K_{adj} \quad (6)$$

In the equation (6) K_{adj} is the modular ratio of various types of aircraft hour performance which is calculated by the following formula:

$$K_{adj} = \frac{A_{hour}^{i}}{A_{hour}^{AN-2}} \quad (7)$$

In the equation (7) A_{hour}^{i} is the hour performance of i-th type of aircraft, A_{hour}^{AN-2} is the hour performance of the An-2 aircraft taken as a comparison base. In addition, when performing aviation chemistry, the area of cultivated land is also taken into account. The criterion for passengers and cargo transportation is the volume of traffic. The main indicators that characterize the performance of the airport are the number of take-offs and landings served, as well as the number of shipments divided by type and destination. An essential role in the calculation of the profitability index is played by the utilization factor of aircraft in the flight hours. It can be calculated by the formula:

$$K_{W}^{i} = \frac{W_{jh}^{i}}{T_{calendar}} \quad (8)$$

In the equation (8) W_{fh}^{i} is the average annual flying hours per one aircraft of the i-th type, $T_{calendar}$ is the annual calendar fund of time in hours

(365 × 24 = 8760 hours). In turn, the utilization factor of aircraft is greatly influenced by the percentage of aircraft serviceability - the ratio of flying hours in good condition to the total number of aircraft hours. It should be borne in mind that even in good condition, aircraft can stand idle. Downtime in good condition includes, in addition to parking in intermediate and final airports and reserve, downtime due to meteorological conditions - periods of forced breaks in the functioning due to inconsistency between actual weather conditions and meteorological minima of the aircraft or aerodrome. The downtime due to meteorological conditions negatively affects the coefficient of aircraft usage per hour productivity, which is expressed by the formula:

$$K^{i}_{Ahour} = \frac{A^{i}_{hour}}{A^{i(\max)}_{hour}} \qquad (9)$$

In the equation (9) A^{i}_{hour} and $A^{i(\max)}_{hour}$ are achieved and maximum possible hourly total productivity of the i-*th* type of aircraft respectively.

We will illustrate the effect of meteorological conditions on the small aircraft performance using example of the METAR weather report for the period from 1 to 30 November 2015. In Fig. 6 there is an analysis of statistical data about actual weather in the Kiev area (Borispol airport) for the specified period.

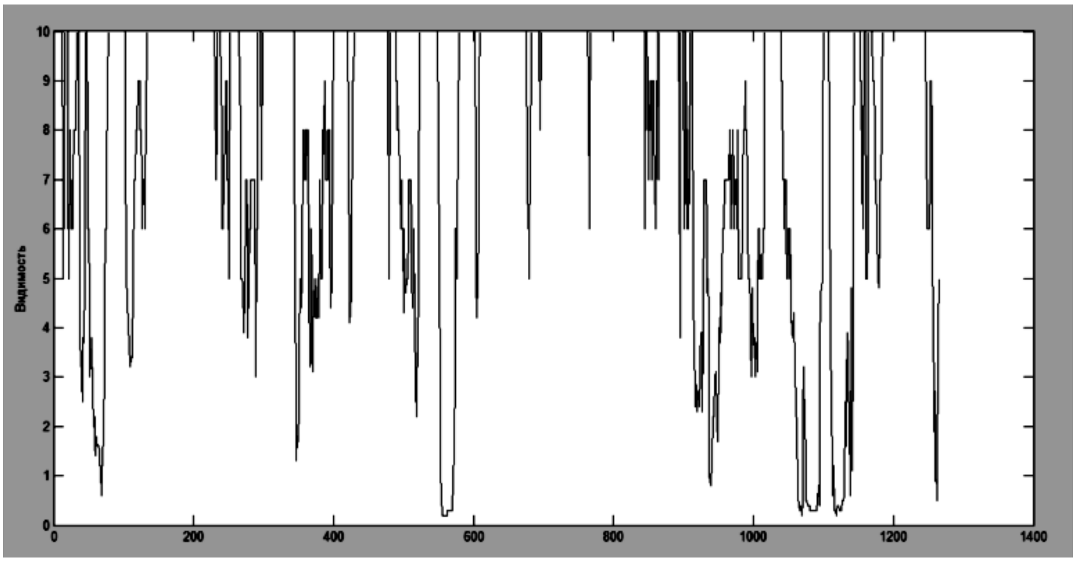


Fig. 6 Horizontal visibility in the Boryspil Airport area in the period from 1 to 30 November 2015

Such a parameter as horizontal visibility in kilometers was considered. It follows from Fig. 6, that 96 out of 1265 time periods (30 minutes each) were unsuitable for VFR flights in the take-off and landing zone in the conditions of flat and hilly terrain (horizontal visibility is less than 2000 meters) and 233 periods were unsuitable for VFR flights in mountainous terrain - (horizontal visibility is less than 5000 meters). Meanwhile, if the aircraft were equipped for IFR cat. I landing, there would be only 64 non-flying periods (horizontal visibility of less than 800 m). Cat. III landing would give us 0 non-flying periods. It can be concluded that the introduction of the presented method of horizontal and vertical aircraft guidance will reduce by 30% the number of non-flying meteorological periods with minimal financial and time costs.

6. Conclusions

The algorithm for the formation of virtual reference surfaces for calculating the horizontal and vertical aircraft deviations aircraft from the desired trajectory allows providing technical conditions for an instrument landing by GNSS signals at minimal costs. The ability to perform an instrumental landing allows crew to switch from VFR to IFR flights if needed, which reduces the number of non-flying meteorological periods by 30% and significantly improves performance.

The algorithm of autonomous integrity control, also considered in the article, allows monitoring integrity in the landing area using ground-based station with 4 visible navigation satellites of one system. It is shown that in 12% of cases 4 visible satellites provide sufficient accuracy for completing the landing, while standard integrity control algorithms give a non-alternative failure under such conditions.

The potential use of a multisystem navigation receiver for improving navigation efficiency in conditions of limited satellites availability is illustrated.

Thus, the considered algorithm of integrity monitoring reduces the number of satellite navigation system failures and also contributes to increasing of flight performance and navigation efficiency.

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Підвищення ефективності навігації літального апарату під час посадки за допомогою супутникової навігаційної системи

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Мета: У цій статті представлено два алгоритми, що дозволяють підвищити ефективність навігації повітряного судна під час заходу на посадку за сигналами супутникової навігаційної системи. Перший алгоритм описує створення в просторі віртуальних опорних площин за координатами чотирьох точок на злітно-посадковій смузі та подальше обчислення горизонтального та вертикального кутового відхилення літального апарату від них. Другий алгоритм описує автономний контроль цілісності навігаційного поля в районі аеродрому за наявності в зоні видимості чотирьох супутників однієї системи. **Методи дослідження**: Використовувались методи планування експерименту, методи аналітичної геометрії та лінійної алгебри. **Результати:** Отримано нові експериментальні дані. **Обговорення:** Результати експериментального дослідження першого алгоритму показали принципову можливість обчислення відхилень літального апарату вказаним способом. Показано, що впровадження запропонованої технології дозволить підвищити ефективність навігації повітряних суден малої авіації під час посадки на аеродромах, які наразі не обладнані радіонавігаційними засобами для інструментальної посадки. Дослідження другого алгоритму показало, що зазначеним способом можливо зменшити кількість відмов супутникової навігаційної системи, що також позитивно впливає на ефективність навігації. Ці результати можуть бути використані у авіакосмічній галузі для зменшення кількості нельотних періодів повітряних суден малої авіації.

Ключові слова: глобальна навігаційна супутникова система; ефективність навігації; інструментальна посадка; посадка літального апарату; точна посадка.

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Повышение эффективности навигации воздушного судна во время посадки при помощи спутниковой навигационной системы

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Цель: В данной статье представлены два алгоритма, позволяющие повысить эффективность навигации воздушного судна при заходе на посадку по сигналам спутниковой навигационной системы. Первый алгоритм описывает создание в пространстве виртуальных опорных плоскостей по координатам четырех точек на взлетно-посадочной полосе и последующее вычисление горизонтального и вертикального отклонения летательного аппарата от них. Второй алгоритм описывает автономный контроль целостности навигационного поля в районе аэродрома при наличии четырех спутников в зоне видимости. **Методы исследования:** Применялись методы планирования эксперимента, аналитической геометрии и линейной алгебры. **Результаты:** Получены новые экспериментальные данные. Обсуждение: Результаты экспериментального исследования первого алгоритма показали принципиальную возможность вычисления отклонений летального аппарата указанным способом. Показано, что внедрение предложенной технологии позволит повысить эффективность навигации воздушных суден малой авиации во время посадки на аэродромы, которые в настоящее время не оборудованы радионавигационными средствами для инструментальной посадки. Исследование второго алгоритма показало, что предложенный способ позволяет уменьшить количество отказов спутниковой навигационной системы, что также положительно влияет на эффективность навигации. Эти результаты могут быть применены в авиакосмической отрасли для снижения количества нелетных периодов для воздушных суден малой авиации.

Ключевые слова: глобальная навигационная спутниковая система; инструментальная посадка; посадка летательного аппарата; точная посадка; эффективность навигации.

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