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Оценка погрешностей измерения навигационно-посадочных параметров с использованием псевдоспутников

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В настоящий момент существенное количество региональных аэродромов не имеют достаточного места для наземного навигационного оборудования. Это может привести к нежелательным последствиям при посадке воздушного судна (ВС) при слабом визуальном контакте экипажа со взлётно-посадочной полосой (ВПП). Система псевдоспутников способна повысить безопасность полетов на этапе посадки в сложных метеорологических условиях на региональных аэродромах без использования индикатора на лобовом стекле (ILS) после оценки погрешностей навигационно-посадочных параметров. Система псевдоспутников может быть использована для повышения безопасности полётов на этапе посадки в сложных метеорологических условиях на региональных аэродромах. Эта система состоит из контрольно-корректирующей станции и псевдоспутников, которые работают в определённых частотных диапазонах.

При использовании этой системы на воздушном судне устанавливается плановый навигационный прибор ПНП-72, который выдаёт основную навигационную информацию с заданной точностью. Это позволяет пилотам использовать более точную информацию и выполнять безопасный заход на посадку и посадку ВС на ВПП даже при слабом визуальном контакте с ней.

Таким образом, использование системы псевдоспутников может помочь решить проблему недостаточного количества наземных навигационных средств на региональных аэродромах. Это позволит обеспечить более точное определение местоположения ВС и улучшить качество навигационной информации, предоставляемой экипажу.

Применение системы псевдоспутников может стать альтернативой использованию дорогостоящих и сложных систем ILS, особенно на небольших аэродромах, где установка таких систем может быть нецелесообразной или экономически невыгодной.

Однако для успешного внедрения и эксплуатации системы псевдоспутников необходимо провести дополнительные исследования и испытания, чтобы определить оптимальные параметры работы системы, а также разработать соответствующие нормативные документы и процедуры для обеспечения безопасности полётов.

Ключевые слова: псевдоспутники, безопасность полетов, GPS-спутники, удаленные аэродромы, спутниковые навигационные системы ГЛОНАСС.

Estimation of measurement errors of navigation and landing parameters using pseudosatellites

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At the moment, a significant number of regional airfields do not have sufficient space for ground navigation equipment, this can lead to undesirable consequences when landing an aircraft with a weak visual contact of the crew with the runway. The pseudo-satellite system is able to improve flight safety at the landing stage in difficult meteorological conditions at regional airfields without using ILS (indicator on the windshield), after evaluating errors in navigation and landing parameters. The pseudo-satellite system can be used to improve flight safety at the landing stage in difficult meteorological conditions at regional airfields. This system consists of a control and correction station and pseudo satellites that operate in certain frequency ranges.

When using this system, the PNP-72 scheduled navigation device is installed on the aircraft, which provides basic navigation information with a given accuracy. This allows pilots to use more accurate information and perform a safe approach and landing of the aircraft on the runway, even with weak visual contact with it.

Thus, the use of a pseudo-satellite system at regional airfields can significantly improve flight safety at the landing stage, especially in difficult meteorological conditions when the use of ILS is impossible. The use of a pseudo-satellite system can also help solve the problem of an insufficient number of ground navigation aids at regional airfields. This will allow for a more accurate determination of the aircraft's location and improve the quality of navigation information provided to the crew.

The use of pseudo-satellites could be an alternative to expensive and complex ILS systems, especially at small airfields where the installation of such systems may be impractical or not economically viable.

However, for the successful implementation and operation of the pseudo-satellite system, additional research and testing is necessary to determine the optimal parameters of the system, as well as to develop appropriate regulatory documents and procedures to ensure flight safety.

Keywords: pseudo-satellites, flight safety, GPS satellites, remote airfields, GLONASS satellite navigation systems.

Introduction

Ground pseudo-satellites for aircraft navigation are usually called ground stations of differential correction (GSDC) or GNSS (global navigation satellite system) base stations. They play an important role in improving the accuracy and reliability of airspace navigation:

– operation of GSDC. GSDC are located on the earth's surface and are equipped with high-precision GNSS signal receivers (e.g. GPS, GLONASS). These stations continuously receive signals from satellites and then correct them to eliminate errors associated with atmospheric and other factors that may affect navigation accuracy;

– correction transmission. Ground stations transmit corrections in real time via radio communications or data networks to navigation receivers installed on board of the aircraft. This allows aircraft to refine their coordinates and improve navigation accuracy to several centimeters [1];

– accuracy improvement. The use of GSDC can significantly improve the accuracy and reliability of airspace navigation. This is especially important for takeoffs, landings, approaches to airports and other flight phases where accuracy plays a decisive role for the safety [2];

– ionospheric effect elimination. GSDC can help eliminate errors caused by the Earth's ionosphere, which can significantly improve navigation accuracy.

The solution of the optimization problem and the choice of solution methods depend on the formation of the objective function, as well as the optimization of the criterion used [3].

Optimization of pseudo-satellite placement

The choice of the objective function is based on the dependence of the magnitude of the errors in measuring the aircraft coordinates on the values of the geometric factor (GF) [4]. Thus, the accuracy of determining navigation and time parameters using satellite navigation systems (SNS) can be estimated through geometric factors (GF). The horizontal geometric factor HDOP allows determining the accuracy of determination of horizontal coordinates (Fig. 1), and to estimate the accuracy of determination of the vertical coordinate, i.e. the height, the vertical geometric factor VDOP is used (Fig. 2).

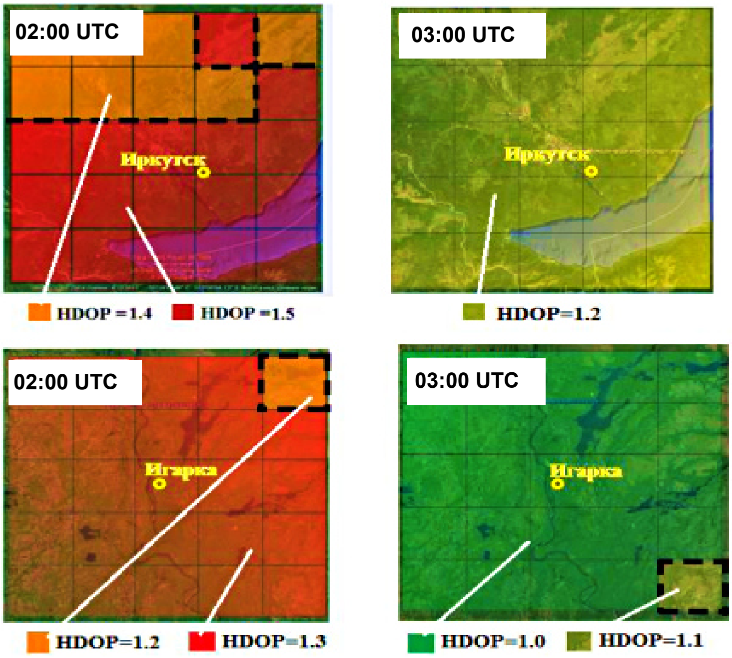

Рис. 1. Поле точности GPS по коэффициенту снижения точности в горизонтальной плоскости (HDOP)

Fig. 1. GPS accuracy field by the coefficient of accuracy reduction in the horizontal plane (HDOP)

It is important to emphasize that the use of pseudo-satellites (PS) has a significant influence on the reduction of vertical geometric factor in solving the navigational problem [5]. Since the precise altitude measurement requirements are particularly important during the landing phase, the PSshould be positioned so that the accuracy of the altitude determination is optimal throughout the entire landing trajectory [6]. Thus, as the target function when solving the problem of finding the optimal location of the PS in the airfield area, we will use the average value of the vertical GF VDOP along the entire landing trajectory:

$$VDOP_{\text{СР}}\left(B_{\text{ПС}}L_{\text{ПС}}H_{\text{ПС}}\right) \rightarrow min, \tag{1}$$

where $B_{ps}L_{ps}H_{ps}$ – geodetic coordinates of the PS. For most airfields, landing on the runway can be carried out from two opposite landing courses. Taking this factor into account, the PS should be positioned so that the average VDOP becomes minimal for both landing trajectories, starting from the glide path approach points and ending with the runway touchdown points (Fig. 3). Taking this fact into consideration, expression (1) will take the form:

$$\frac{1}{n}\sum_{1}^{n} VDOP_{\text{СР}}\left(B_{\text{ПС}}L_{\text{ПС}}H_{\text{ПС}}\right) \rightarrow min, \tag{2}$$

where n is the number of landing trajectory points in which the GF is calculated. Taking into consideration small GF changes at nearby points, it is sufficient to use 25–30 uniformly distributed points to calculate the average GF along the landing trajectory. Consequently, it is proposed to consider the optimal PS placement as the one that ensures the minimum average VDOPav value for the entire landing trajectory, determined by expression (2). Since, due to the orbital motion of the PS, time variations in the geometric factor are observed in the airfield area, then when solving the optimization problem, the average VDOP value along the entire landing trajectory used as a criterion should also take this feature into account. Expression (2) will be:

$$\frac{1}{n}\sum_{1}^{n} VDOP_{CPi}\left(B_{ПС}L_{ПС}H_{ПС}\right) \to min \quad , \qquad (3)$$

where i is the moment in time for which the average VDOP value along the landing trajectory is calculated.

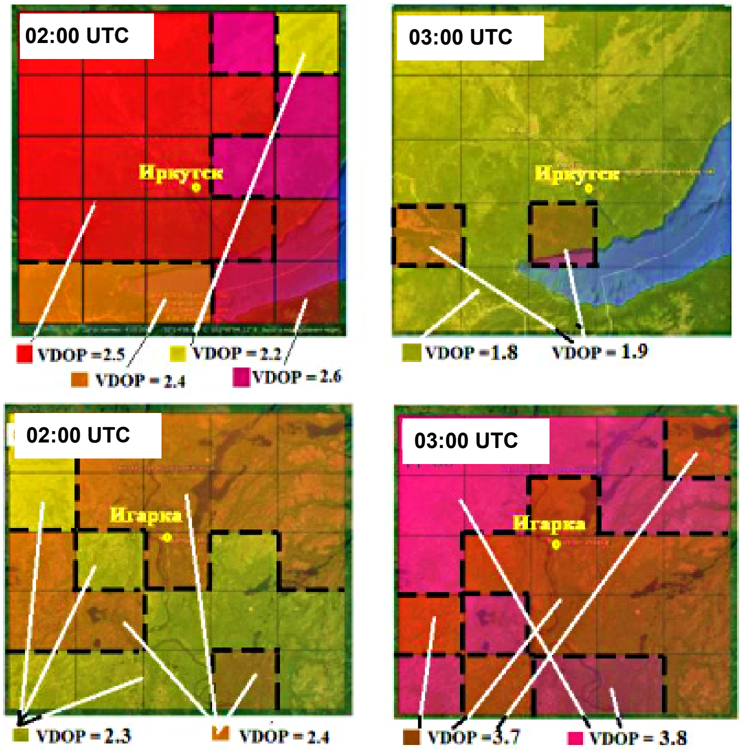

Рис. 2. Поле точности GPS по коэффициенту снижения точности
в вертикальной плоскости (VDOP)

Fig. 2. GPS accuracy field by vertical plane accuracy reduction factor (VDOP)

The duration of a complete cycle of GLONASS orbital motion is approximately eight days (691200 s). Since the temporary changes in VDOP are quite slow, to solve this problem it is sufficient to select a time interval for calculating VDOP of about 10 min (600 s). To take into consideration the entire recurrence period of the GLONASS orbital structure, it is necessary to divide 691200 by 600, which is equal to 1152 values [7].

Methods for creating a ground equipment system for the landing system and on-board equipment of the aircraft, as well as methods for high-precision synchronization of several pseudo-satellites are being studied. This system is the local-area augmentation system (LAAS) [8]. The LAAS ground equipment includes:

– a reference station for differential correction of navigation signals (CNS);

– PS transmitters, the signal of which is modulated by a ranging code;

– a control receiver that ensures verification of the signal emitted by the PS according to several criteria;

– signal power, shift of the time scale of the ranging code, structure and content of the transmitted digital information.

The main features of the presented version of the construction of the ground segment of the LAAS:

– synchronization of the time scales (TS) of the PS directly from the output ranging radio signals of the PS;

– combination of the functions of control and synchronization of the PS;

– combination of the receiving device that ensures the formation of differential corrections of the CNS with the receiving device for synchronization of the TS of the PS;

– control of the delay of the ranging signal and the radiated power of each PS over the local network;

– the use of a highly stable reference oscillator (RO) in the base station to maintain synchronization with the CNS in case of temporary absence of reception of signals from the NSC;

– maximum reduction in the cost of the PS for a "painless" increase in their number in the LAAS. The structural diagram of the LAAS is shown in Fig. 3.

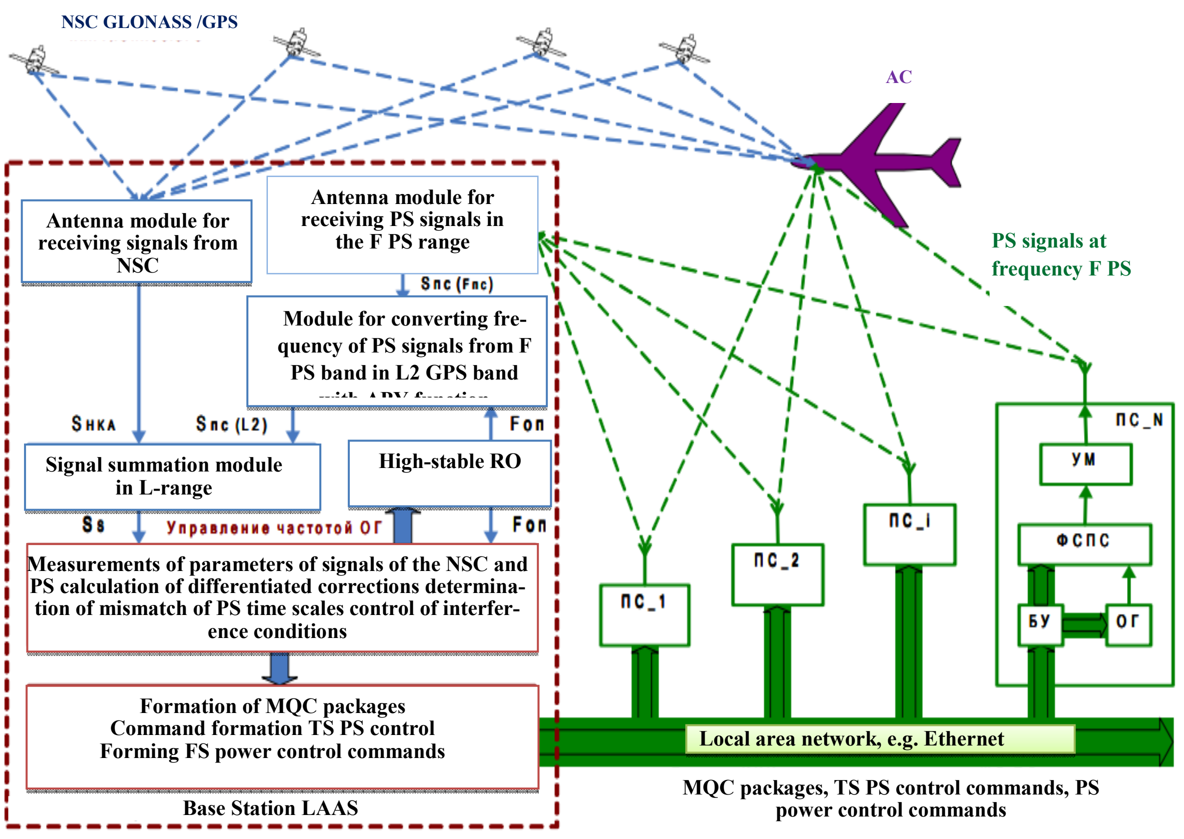

Рис. 3. Структурная схема ЛСПВС

Fig. 3. The structural diagram of the LAAS

The analysis shows that in order to ensure separation of signals from several PS, electromagnetic compatibility of PS signals with ground equipment of the LAAS system, GLONASS/GPS navigation equipment and on-board equipment of the aircraft, as well as to achieve high accuracy of measuring radio navigation parameters (delay of the Doppler frequency shift, phase and phase difference of the carrier frequency signals), it is necessary to use signals for PS that are different from the existing CNS signals [9]. In particular, it is recommended to transmit PS signals at a carrier frequency that is significantly different from the frequencies of the GLONASS/GPS NSC signals, which will ensure frequency separation of these signals [10].

When choosing the frequency range of the PS signal, it is also important to take into consideration the location of the antenna for receiving PS signals on board the aircraft. There are two options for placing the antenna: in the upper and lower parts of the fuselage [11].

Improving navigation accuracy

The overall effect of using ground-based pseudo-satellites for aircraft navigation is a significant improvement in the accuracy and safety of flights, which is especially important in civil and military aviation. This technology allows pilots and automatic aircraft control systems to accurately determine their position and follow a given route with a high degree of confidence [12].

Ground-based pseudo-satellites improve navigation accuracy by providing additional sources of data and corrections to GPS (or other satellite navigation system) receivers, which helps to improve positioning accuracy [13].

Ground-based pseudo-satellites are placed at known locations with known coordinates. They can observe signals from satellites and calculate errors in these signals caused by atmospheric effects or other factors [14]. They then transmit these corrections to GPS receivers, which use them to improve positioning accuracy. Differential positioning systems (DGPS) use a station on the ground, known as a base station, which measures errors in the GPS signals and sends corrections to the ground-based pseudo-satellites (the actual GPS satellites) and receivers on the ground. This allows to improve the accuracy of positioning in a specific territory.

Real-Time Kinematic (RTK): RTK is a method that also uses a base station, but in this case the corrections are transmitted in real time and a receiver on the ground can achieve very high accuracy (up to centimeters) in positioning.

Real-time correction systems. There are various real-time correction systems, such as the Wide Area Augmentation System (WAAS) in the United States or the European Geostationary Navigation Overlay Service (EGNOS) in Europe. They provide corrections to GPS signals via satellites or ground stations.

GPS signal enhancement. To improve the signal in a specific area, GPS signal boosters or distributed antenna can be used.

Use of additional sensors. To improve the positioning accuracy, additional sensors can be used, such as inertial measurement units (IMUs) or magnetometers, to compensate for GPS errors [15].

Local databases and maps. Creating local databases of the area, including information on obstacles, buildings, etc., helps in positioning corrections.

Real-time correction distribution. Ground-based PSs transmit corrections in real time to GPS receivers via a network or radio channel. This allows correction information to be updated continuously and to instantly take into account changes in atmospheric conditions or other factors that cause effect on accuracy.

To improve navigation accuracy, ground-based satellites can integrate data from various sources, such as geodetic measurements, altitude information, meteorological data, etc.

The combination of these factors allows ground-based satellites to increase navigation accuracy and provide more reliable and accurate positioning for GPS receivers and other navigation systems.

The optimal number of satellites depends on several factors, including navigation purposes, accuracy, reliability and confidence in positioning. It is important to understand that the more satellites are used in the positioning process, the higher the probability of achieving more accurate results. However, there is an optimal number of satellites that can be used to ensure sufficient accuracy and reliability, namely:

– minimum number of satellites for 2D positioning: at least 3 visible satellites are required to determine a two-dimensional (latitude and longitude) position. This ensures positioning on the Earth's surface;

– minimum number of satellites for 3D positioning: for 3D (latitude, longitude and altitude) positioning, a minimum of 4 visible satellites are required. These are three satellites to determine the horizontal position and the fourth for the altitude.

To increase positioning accuracy and reliability, it is recommended to use more visible satellites. Usually, the more satellites, the better [15].

Thus, the optimal number of PS depends on the specific requirements of the task. In most situations, more than 4 visible satellites provide good accuracy, but aviation may require additional satellites to improve the reliability and accuracy of positioning.

Let us analyze the impact of the number of optimally placed network stations on the parameters of the integrated navigation system in the studied airspace area around the Baikit airfield. In this case, the task of determining the optimal positions of stations (the possibility of connecting up to five stations was considered) was solved in stages, i.e. after determining the optimal position of the first station, the optimal position of the second station was determined, then the third, and so on. The results obtained show that an increase in the number of stations leads to a decrease in the average VDOP value and the range of its changes.

The table shows the values of the average VDOP along the landing trajectory calculated for the time moment 11:30 UTC 05/07/2021 both in the absence of PS (column 2) and with their different numbers. The selected moment in time is characterized by one of the worst values of VDOP = 2 in the area of the Baikit airfield over the entire 8-day interval of GLONASS operation.

VDOP with different amount of PS (Baikit)

	GLONASS	GLON+1PS	GLON+2PS	GLON+3PS	GLON+4PS	GLON+5PS
Averadge VDOP	2	1,311	0,973	0,870	0,791	0,742
Win without PS, %	–	35	52	57	61	63

According to the table, the use of placement optimization allows reducing VDOP as follows: when using one PS - by 35%, two PS - by 52%, three PS - by 57%, four PS - by 63%. A further increase in the number of PS in the network does not lead to a significant improvement in the vertical geometric factor and the accuracy of determining the flight altitude of the aircraft. Thus, although the use of more than four PS to improve the accuracy of determining the flight altitude of the aircraft is impractical, this increases the reliability of the system.

Conclusion

The use of PS in navigation and landing systems allows to increase the accuracy of defining navigation parameters and improve the reliability of navigation support. The use of such systems is especially actual for airfields with limited ground infrastructure capabilities and in difficult meteorological conditions.

The use of pseudo-satellites in navigation and landing systems also helps to reduce dependence on global navigation satellite systems, such as GPS and GLONASS, and to increase the autonomy of navigation support.

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