AEROSPACE SYSTEMS FOR MONITORING AND CONTROL

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PERFORMANCE ANALYSIS OF POSITIONING BY NAVIGATIONAL AIDS ACCORDING TO RNAV REQUIREMENTS

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Abstract

Nowadays the problem of primary positioning system of aircraft malfunction became valuable due to influence of interference and unintentional jamming of radio signals. Selection of an efficient stand-by positioning system is an important task of a modern flight management system. Stand-by positioning systems have to meet all requirements of performance-based navigation according to specification is used in the airspace. The paper is aimed at the analysis of available positioning algorithms and systems for use in civil aircraft in case of primary positioning system malfunction. Positioning by navigational aids is considered as the main alternative in case of primary system malfunction for Ukrainian airspace, due to a sufficient network of ground stations. Also, results of performance analysis in form of contours of correspondence with requirements of area navigation specifications are presented in the paper for Ukrainian airspace at FL 290. Obtained results may be useful at pilot training for visualization of areas unsupported for navigation and for ground navigational aids development process.

Keywords: Navigational aids, APNT, DME, VOR, DME/DME, positioning, stand-by, aircraft, civil aviation

1. Introduction

Nowadays, aviation is one of the fastest-growing types of transport. Numerous advantages of air transport, in comparison with other types, lead to a constantly growing interest in air transport services. World air traffic statistics show a steady increase in demand for air services, as a result of it, the number of flights is growing rapidly. According to preliminary forecasts, air transport services will double by 2034 compared to 2016 [1]. However, the rapid development of air transport affects the congestion of airspace, the capacity of which is limited.

Addressing the limited airspace and meeting the needs of air transport is a major challenge facing the air transport system in the future. The only one effective way to increase capacity is to introduce new air traffic concepts, including the introduction of Free-Flight zones and the introduction of new aircraft traffic schemes based on more accurate navigation specifications in the airport's airspace volume.

Increased requirements for accuracy of positioning in the airspace and the introduction of new more accurate navigation characteristics are noted in global [2] and regional aviation development plans [3]. Improving the accuracy of navigation definitions is a key task in supporting the growth of air traffic in terms of ensuring the required level of air safety. Airplane localization in the airspace is one of the most important tasks of navigation. An accuracy of airplane coordinates measuring has a direct connection with the efficiency of air navigation and safety of air transportation.

According to the Performance-based navigation concept [4], each airplane has to identify its location in air space under specific requirements valid in airspace volume used. Following all area navigation regulations is to guarantee safe air space usage and admit the required level of flight safety.

Today, the Global Navigation Satellite System (GNSS) plays a key role in determining the coordinates of the location of the aircraft, approved at the international level by the International Civil

Aviation Organization [5]. This is due to the highest level of availability on a global scale, high values of integrity, continuity, and positioning accuracy compared to other available methods. However, GNSS has certain disadvantages, such as poor geometry of the satellite segment at a certain point in time, which reduces the accuracy of positioning and high dependence on artificial interference, which in some cases may make it impossible to determine the coordinates of the location. GNSS is sensitive to interference from other electronic devices and natural phenomena. Because the GNSS space segment is at a considerable distance from users, the GNSS signal strength in the user segment is low and electronic equipment with a sufficient level of power can completely interfere with positioning [6]. Besides, there are a large number of systems available on the market that can interfere with the GNSS frequency range. Small size and low cost have made them popular with today's users to ensure their privacy. Such systems violate the law on radio frequency use, but their area of operation is small, which makes it impossible to detect and block them [6]. Accordingly, this problem is relevant and will remain so shortly. The issue of determining the aircraft's location is especially relevant at the stage of take-off and landing of the aircraft, as the accuracy and availability of positioning depend on the safety of air transportation. Besides, an aircraft at low altitude is vulnerable to interference, the source of which may be on Earth. Poor positioning accuracy can lead to an accident and even a catastrophe.

The International World Aviation Society has been working for many years to find optimal alternatives to GNSS positioning methods (Fig.1) to ensure continued flight by instrument flight rules in the event of a GNSS on-board equipment failure.

The paper is aimed to analyze all available stand-by on-board positioning methods and systems which can be used for civil aircraft navigation in case of primary system (GNSS) malfunction.

2. Stand-by positioning facility of airplane

Inertial navigation systems and algorithms of positioning by navigational aids are commonly used as alternative positioning systems on board of civil aircraft. The use of the inertial navigation system is limited in time due to the accumulation of error [7].

Numerous fundamental studies have proven the relevance of using ground-based area navigation systems as alternative positioning tools. Positioning by ground beacons is seen as an alternative to satellite navigation in global air transport development plans.

Algorithms of positioning by navigational aids are used in air transport today use only a pair of ground beacons simultaneously to determine coordinates, which significantly limits their accuracy.

Time of Arrival (TOA) positioning algorithm uses the measurement of range to certain navigation points by directly measuring the time of passage of the navigation signal in space or measuring frequency (FOA – Frequency of Arrival) or phase (POA – Phase of Arrival) offsets in the navigation signal, artificially associated with range [8]. The method is based on the known speed of radio waves propagation in the space. A practical implementation of the TOA considers sensors that generate a navigation signal that propagates in the airspace from the objects and returns back to the sensor measuring the range to the object. Another type of sensor exclusively receives navigation signals, and the time of transmission of the navigation signal from a certain navigation point is considered to be known. The distance to the source of the navigation signal can be determined by measuring the power. In this case, the transmitted power and the mathematical model of signal attenuation during propagation in space are known. The method of measuring the range by the power of the received navigation signal (RSS - Received Strength of Signal) is widely used in modern digital data networks. TOA is used in positioning by pair of Distance Measuring Equipment (DME). DME measures a range between airplane and ground transponder.

Angle of Arrival (AOA) algorithm is based on using the angles of direction to fixed in space navigation points [9]. In common, such sensors are based on certain directions of arrival of the navigation signal. To do this, use directional antenna systems that scan the space mechanically or electrically. AOA is used for positioning by angle data from VHF Omnidirectional Ranging (VOR) equipment or by data from Automatic Directional Finder (ADF). ADF measures bearings to Non-directional Beacons. Due to rapid.

Low level of angular data acuracy is the main perils of AOA development. AOA in comparison to TOA support much less accuracy level, thus ground network of VOR and NDB are going to be shout down in near future.

In the case of location of both VOR and DME at the same waypoint, an AOA/TOA (or VOR/DME) positioning algorithm can be used. In common VOR/DME navigation is mostly used in Standard

Terminal Arrival Route (STAR) and Standard Instrument Departure (SID) Route.

Also, hyperbolic methods are widely used in civil aviation. Hyperbolic algorithms are based on the properties of the hyperbola, which has a constant difference in distances between two focus points [10]. As a physical parameter, this group of methods can use the difference between the time of fixation of the navigation signal (TDOA – Time Difference of Arrival) or the phase of the navigation signal (PDOA – Phase Difference of Arrival)[11]. Nowadays TDOA algorithms are widely used in multilateration systems.
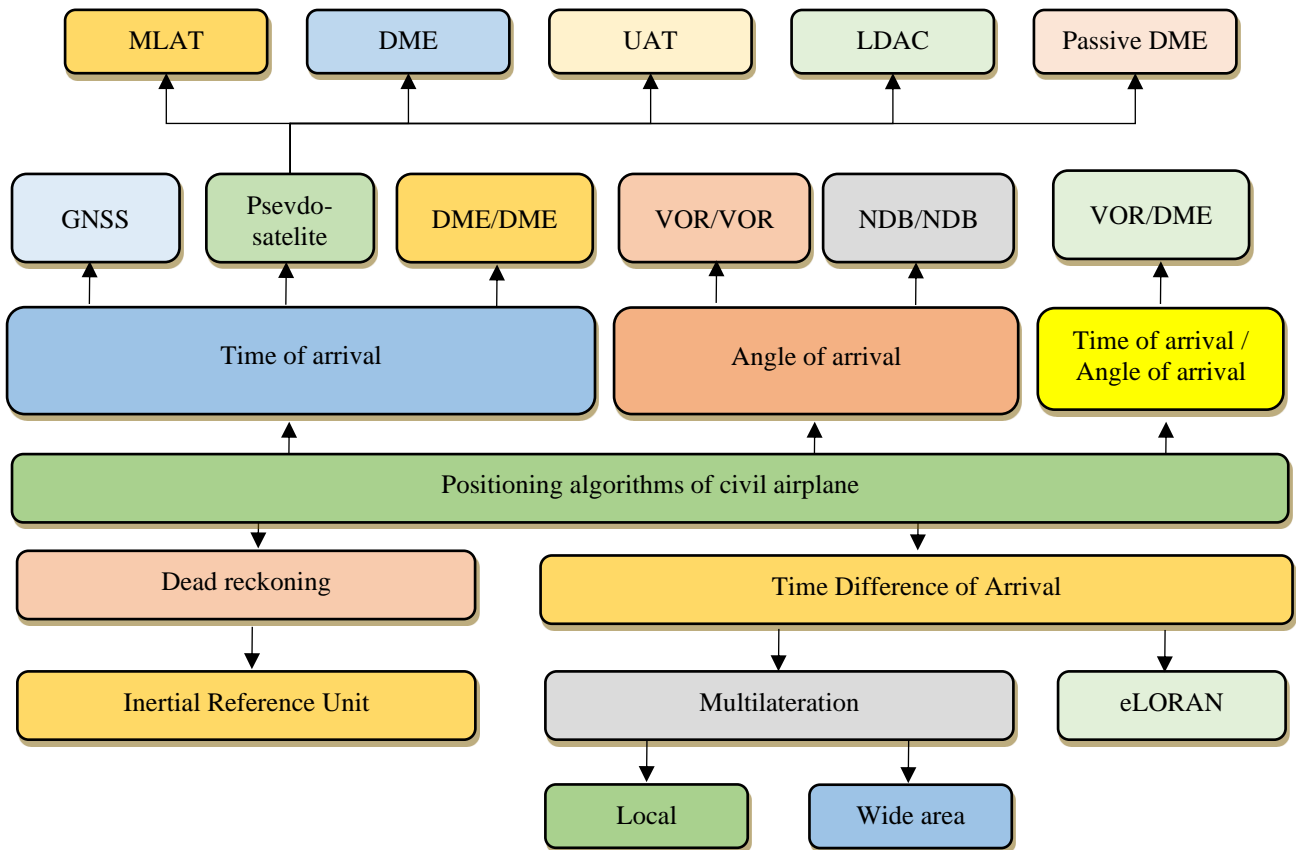

Fig. 1. Basic classification of positioning algorithms and systems of civil airplane

Passive multilateration systems are an accurate means of positioning the aircraft in the airport area. Wide Area Multilateration system consists of a number of terrestrial receivers of on-board transponders of mode S and ADS-B. Each ground station-receiver fixes the time of signal reception and sends it to the control station. TDOA algorithms in the control stations determine the coordinates of the aircraft by the time of signal fixation by different receiving stations. The received location of the aircraft is sent on board the aircraft using a traffic sharing service.

In common, pseudo-satellite positioning systems are based on the use of a TOA algorithm similar to the principle of positioning in GNSS. The system uses pseudo-satellites located at a short distance from the receivers (the distance does not exceed several hundred km), compared to GNSS, located on the Earth's surface. Previously, pseudo-satellite were considered as additions to GNSS. However, pseudo-satellite are able to work independently, in case of complete unavailability of GNSS, which makes them important as a stand-by positioning approach. Compared to GNSS, Pseudo-satellites has many advantages, including low cost, no influence of the ionosphere and troposphere on the radio waves propagation, the power of the navigation signal is sufficient to ensure accurate positioning.

Variety of disadvantages of pseudo-satellites include multipath and radio waves interference, which can completely change the pseudo-distances defined in the system. Today, pseudo-satellite within the APNT concept considers a multilateration system, a network of DME and UAT terrestrial beacons as a

pseudo-satellite segment located on the Earth's surface.

Another promising positioning technology is the L-band Digital Aeronautical Communication System (LDACS) for digital data transmission and ground-to-air communication. LDACS considers two options for the practical implementation of LDACS1 and LDACS2. LDACS1 uses frequency division of duplex data channels using OFDM (Orthogonal Frequency-Division Multiplexing). LDACS2 is a narrowband communication system with one carrier frequency and time division of a duplex channel. The main task of LDACS is to provide an additional line of communication between the aircraft and the ATC controller and to provide access requirements for aeronautical information. The most promising of the LDACS is LDACS1 technology. Numerous scientific studies, supported by the results of experimental tests, indicate the possibility of using LDACS1 signals to position the aircraft with an accuracy of 15 m [12]. However, results of practical study [13] indicate possible problems of the influence of DME interference on the determination of coordinates by LDACS1.

Nowadays, distance measuring and passive ranging (DMPR) approach is based on the use of the fundamental principles of DME operation to measure distances. The DMPR uses the existing network of DME ground stations [14]. In addition, DMPR contains ground stations, which, similar to DME on-board equipment, generate request signals in the DME system, synchronized at certain intervals. DME ground stations, in turn, receive these signals and generate response signals. The on-board equipment receives request signals for synchronization, as well as receives response signals and records the time of their reception. The range from the DME ground stations to the aircraft is determined by the known interrogation time, the coordinates of the interrogation ground station and the DME, as well as the time interval of the response signal generation.

DMPR reduces the congestion of the DME ground infrastructure because each user receives the distance to the DME ground station without a request signal. In addition, the DMPR concept can operate independently of the conventional use of DME beacons and meet the requirements associated with the growth of air traffic. According to global trends, in the future it is expected to load DME in 260 aircraft simultaneously.

However, the presented method has two main disadvantages:

- the need for accurate time synchronization of ground stations;
- to solve the navigation problem, at least 3 DMEs must be available in the DMPR for positioning in the horizontal plane, as 1 DME must compensate for the clock error in the onboard part of the equipment.

3. Performance-based navigation

Nowadays, an air navigation system is based on area navigation methods. Highly fast developing of air transportation at the beginning of 80's required to switch from classical to area navigation.

Classical navigation is based on wide usage of angles and distance from NDB, VOR, and DME for airplane path detection. Area navigation (RNAV) is based on measuring the airplane positioning. The airplane positioning is supported by specific sensors or algorithms, action of which is limited to a certain area in space.

In common, there are three main types of area navigation: 2D, 3D, and 4D. The implementation of each of the RNAV methods depends on performance of the on-board navigation equipment, in particular parameters of accuracy, integrity, continuity in accordance with the requirements of particular airspace. The main requirements for characteristics of area navigation systems are defined by performance-based navigation (PBN) manual [3]. The PBN concept is the result of a transition from sensor-based navigation to performance-based navigation.

Requirements for positioning accuracy within area navigation are formulated in the navigation specifications. RNP specifications require continuous performance monitoring of on-board equipment and alarming in case of exceeding their permissible limits [15]. RNAV specifications do not require alarming [3]. The type of navigation specification is determined by the number in nautical miles, which reflects the maximum positioning tolerance.

4. Evaluation of positioning by navigational aids for Ukrainian airspace

In particular, within Ukrainian airspace positioning by navigational aids are considered as a main stand-by approach. Therefore for numerical demonstration, we estimate correspondence of positioning approaches by navigational aids with requirements of RNAV. Ukrainian navigational aids ground network, on May 2020, includes 9 DMEs (BAH, KSN, KVR, RVN, STB, TER, UZH, VIN, YHT) and 8 VOR/DMEs (BRP, DNP, IVF, KHR, KVH, LIV, ODS, SLV) locates over the country [16].

Level of signals from Ukrainian navigational aids network is considered enough for their operation within standard service volume. During a study, we divide the whole airspace volume into a set of elementary cells. Positioning performance is evaluated for each cell separately and is considered constant within each cell [17]. In computer-based simulation, we use 110 cells in East-West directions and 59 in North-South. The number of cells within Ukrainian airspace boundaries is 3366. The area of each cell is 252 km^2. Also, we use FL 290 (8850 m). Results of positioning performance [18] correspondence with RNAV requirements are represented in fig.2-4 for DME/DME, VOR/DME, and VOR/VOR algorithms based on optimal pair of navigational aids [19].
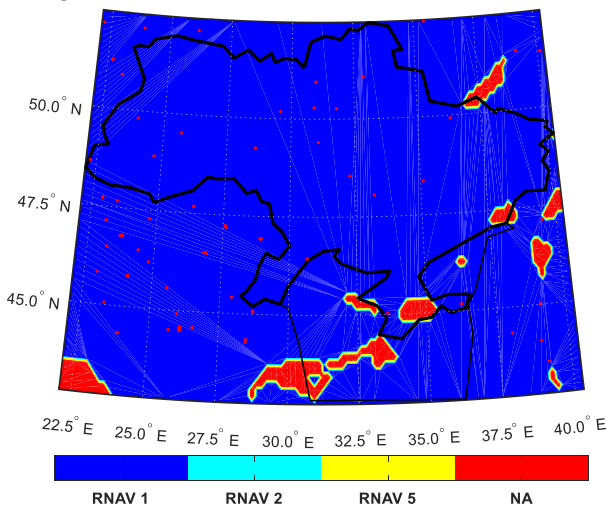

Fig. 2. Evaluation of correspondence of DME/DME positioning performance with RNAV
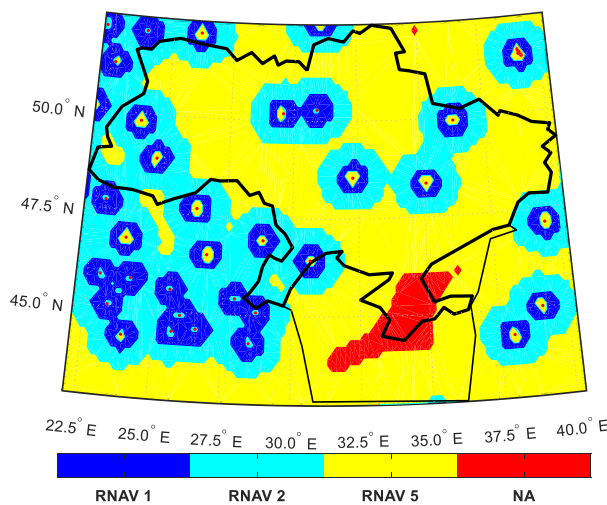

Fig. 3. Evaluation of correspondence of VOR/DME positioning performance with RNAV
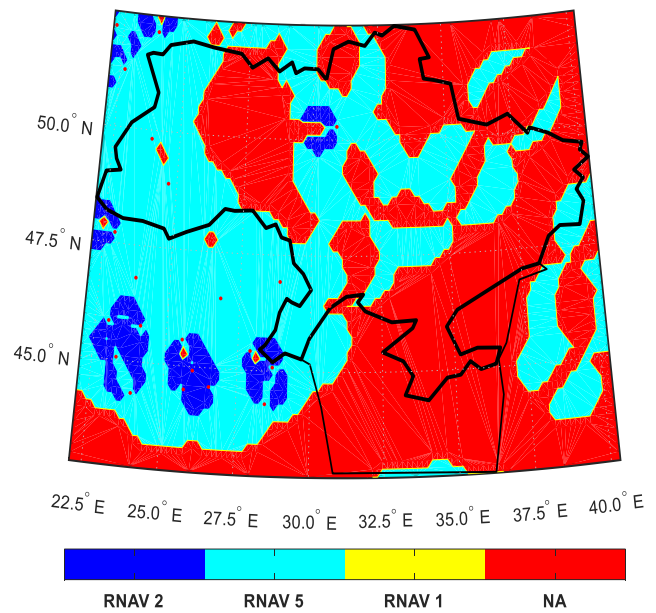

Fig. 4. Evaluation of correspondence of VOR/VOR positioning performance with RNAV

Obtained results indicate that for DME/DME algorithm RNAV 1 requirements are met at 97.36 % (827.9× 10^3 km^2). VOR/DME positioning algorithm supports RNAV 1 only in 6.09 % (51.8 × 10^3 km^2), RNAV 2 in 34.85 % (296.4 × 10^3 km^2), and RNAV 5 in 95.48 % (812 × 10^3 km^2). VOR/VOR is satisfied RNAV 2 requirements only in 1.04 % (8.8 × 10^3 km^2) and RNAV 5 in 45.45 % (386.5 × 10^3 km^2).

8. Conclusions

Results of analysis of alternative positioning algorithms indicate numerous technologies that may be used on-board of aircraft. However, only positioning by navigational aids can be used as a stand-by system in case of primary system malfunction within Ukrainian airspace. Ukrainian navigational aids network includes 17 DMEs and 8 VORs that make it possible to use DME/DME, VOR/DME, and VOR/VOR positioning algorithms.

Obtained results of performance estimation for positioning by navigational aids at FL 290 indicates near full coverage of DME/DME navigation in 97.36 % of airspace correspondence with RNAV 1 specifications requirements. VOR/DME can be used only in 6% of airspace and VOR/VOR does not meet RNAV 1 requirements at all.

Also, obtained results may be useful in the task of air navigation network developing and updating in order to improve service at specific areas with poor performance levels.

References

[1] Aviation Benefits report 2017 (2017). IHLG, 68 p.

[2] Global Air Navigation Plan. 2016 – 2030 (2016). Capacity and efficiency. ICAO, 142 p.

[3] Performance-Based Navigation. Navigation strategy. FAA, 2016. 37 p.

[4] Performance-Based Navigation (PBN) Manual. Doc 9613. ICAO, 2008. 304p.

[5] Global Navigation Satellite System (GNSS) Manual. Doc 9849. ICAO, 2012. 68 p.

[6] Ostroumov I.V. and Kuzmenko N.S., (2019). Main Threats and Solutions for Positioning by Navigational Aids Network. Proceedings of the International Workshop on Conflict Management in Global Information Networks (CMiGIN 2019) co-located with 1st International Conference on Cyber Hygiene and Conflict Management in Global Information Networks (CyberConf 2019). pp. 183-193.

[7] Passaro V., Cuccovillo A., Vaiani L., De Carlo M., and Campanella C.E. (2017). Gyroscope technology and applications: A review in the industrial perspective. Sensors, 17(10), 2284p.

[8] Caffery J.J. (2000). A new approach to the geometry of TOA location. In Vehicular Technology Conference Fall 2000. IEEE VTS Fall VTC2000. 52nd Vehicular Technology Conference (Cat. No. 00CH37152). Vol. 4, pp. 1943-1949.

[9] Xiong L. (1998). A selective model to suppress NLOS signals in angle-of-arrival (AOA) location estimation. Personal, Indoor and Mobile Radio Communications: The Ninth IEEE International Symposium. IEEE. Vol. 1. pp. 461–465.

[10] Ostroumov I.V. (2018). Passive positioning method using distance measuring equipment and automatic dependent surveillance-broadcast data. Proceedings of the National Aviation University. Vol. 75(2). pp. 19-25. DOI: 10.18372/2306-1472.75.13113 .

[11] Zhang C. and Pang K. (2013). Navigation with the broadband mimo-nci-OFDM air-to-ground communications network. Digital Avionics Systems Conference (DASC). IEEE/AIAA. pp. 3C1-1–3C1-10.

[12] Schneckenburger N., Elwischger B., Belabbas B., Shutin D., Circiu M. S., Suess M., Schnell M., Furthner J., and Meurer M. (2013). Navigation performance using the aeronautical communication system LDACS1 by flight trials. Europenian Navigation Conference. pp. 1–9.

[13] Thiasiriphet T., Schneckenburger N., and Schnell M. (2015). Impact of the DME interference on the LDACS1 ranging performance. Proceedings of the 28th International Technical Meeting of the Satellite Division of the Institute of Navigation. Florida, ION, pp. 1446–1467.

[14] Lo S. and Enge P. (2012). Signal structure study for passive ranging system using existing distance measuring equipment (DME). Proceedings of the Institute of Navigation International Technical Meeting. Newport Beach, CA. 11 p.

[15] Ostroumov I.V. and Kuzmenko N.S. (2018). An area navigation RNAV system performance monitoring and alerting. System Analysis & Intelligent Computing: SAIC 2018 1st International Conference of IEEE. pp. 211-214.

[16] Aeronautical Information Publication (AIP) of Ukraine Ukrainian (2020). State Air Traffic Services Enterprise.

[17] Ostroumov I.V., Kharchenko V.P., and Kuzmenko N.S. (2019). An airspace analysis according to area navigation requirements. In Aviation, vol. 23(2). pp. 36-42.

[18] Kuzmenko N.S., Ostroumov I.V., and Marais K. (2018). An Accuracy and Availability Estimation of Aircraft Positioning by Navigational Aids. Methods and Systems of Navigation and Motion Control: MSNMC 2018 5th International Conference of IEEE. 2018. P. 36-40. DOI: 10.1109/MSNMC.2018.8576276.

[19] Ostroumov I.V., Kuzmenko N.S., and Marais K. (2018). Optimal Pair of Navigational Aids Selection. Methods and Systems of Navigation and Motion Control: MSNMC 2018 5th International Conference of IEEE. pp. 32-35. DOI: 10.1109/MSNMC.2018.8576293..

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Аналіз ефективності позиціонування за допомогою навігаційних засобів відповідно до вимог зональної навігаці
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У даний час проблема відмови основної системи позиціонування літального апарату є актуальною внаслідок дії факторів перевідбивання та ненавмисного глушіння радіосигналів під час поширення у просторі. Вибір ефективної системи резервного позиціонування є важливим завданням сучасної системи управління польотом. Резервні системи позиціонування повинні відповідати всім вимогам навігації, що базується на характеристиках, згідно із специфікацією, що використовується у повітряному просторі. Стаття спрямована на аналіз доступних алгоритмів позиціонування та систем для використання на цивільних літаках у разі відмови первинної системи позиціонування. Позиціонування за допомогою навігаційних засобів вважається основною альтернативою у випадку відмови первинної системи для повітряного простору України через достатню мережу наземних станцій. Результати аналізу ефективності у вигляді зон відповідності вимогам специфікацій навігації наведено для повітряного простору України на FL 290. Отримані результати можуть бути корисними при підготовцы пілотів для візуалізації зон, що не підтримують певні навігаційні специфікації, та у процесі модернізації наземної мережі радіонавігаційних засобів України.

Ключові слова: Радіо-навігаційні засоби, APNT, DME, VOR, DME / DME, позиціонування, резервна система, літак, цивільна авіація.

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Анализ характеристик позиционирования навигационными средствами согласно требованиям зональной навигации
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В настоящее время проблема отказа основной системы позиционирования летательного аппарата является актуальной вследствие действия факторов переотражения и непреднамеренного глушения радиосигналов во время распространения в пространстве. Выбор эффективной системы резервного позиционирования является важной задачей современной системы управления полетом. Резервные системы позиционирования должны отвечать всем требованиям навигации, основанной на характеристиках, согласно спецификации, которая используется в воздушном пространстве. Статья направлена на анализ доступных алгоритмов позиционирования и систем для использования на гражданских самолетах в случае отказа первичной системы позиционирования. Позиционирование с помощью навигационных средств считается основной альтернативой в случае отказа первичной системы для воздушного пространства Украины. Результаты анализа эффективности в виде зон соответствия требованиям спецификаций навигации приведены для воздушного пространства Украины на FL 290. Полученные результаты могут быть полезными для подготовки пилотов при визуализации районов не поддерживающих навигациионые спецификации, и в процессе модернизации наземной сети радионавигационных средств Украины.

Ключевые слова: Радио-навигационные средства, APNT, DME, VOR, DME/DME, позиционирование, резервная система, самолет, гражданская авиация.

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