Risk of Mid-Air Collision in a Lateral Plane

Ivan Ostroumov[1][0000-0003-2510-9312], Oleg Ivashchuk[2][0000-0001-5637-0332], Tetiana Shmelova[3][0000-0002-9737-6906] and Sergii Babichev[4,5][0000-0001-6797-1467]

[1, 2, 3]National Aviation University, Lubomira Huzara ave., 1, Kyiv, 03680, Ukraine

[1]`vany@nau.edu.ua`, [2]`iva.oleg2000@gmail.com`,
[3]`shmelova@ukr.net`

[4]Jan Evangelista Purkyne University in Usti nad Labem, Ceske mladeze, 8, Usti nad Labem, 40096, Czech Republic
[5]Kherson State University, Universytetska st. 27, Kherson,73003, Ukraine

[4]`sergii.babichev@ujep.cz`

Abstract. Mid-air collision in air transportation is one of the most dangerous safety categories. The risk of mid-air collision assessment is an important component of aviation safety estimation. Due to the low number of accidents happened, risk of mid-air collision within limited airspace may be estimated by evaluation of its main components. Paper is more focused on assessing the risk of air traffic separation lost in lateral plane based on air traffic deep learning within predefined airspace. Statistical analysis of current air traffic data and geometrical configuration of routes network are used for probability distribution function fitting. Position of airspace users is obtained from location reports coded by Automatic Dependent Surveillance-Broadcast data format, which is received by ground-based software defined radio. Risk of separation lost in the lateral plane is estimated based on density probability distribution function of airplane unintentional deviations. Finally, the risk of a mid-air collision in the lateral plane is estimated by Reich formula for Ukrainian airspace.

Keywords: airplane, mid-air collision, risk, separation lost, air routes, lateral plane, big data, statistics, TUGED.

1 Introduction

Airplane navigation is a key element of successful transport system operation that Mid-air collision is an important problem of air transportation that is connected with limited airspace volume and continuously increasing number of airspace users. The problem of mid-air collision was extremely important in the early 90th due to speed aviation development and lack of collision avoidance technology [1-2]. Speedy development of computer-based systems in 2000 helped to reduce a global statistic of mid-air collisions in civil aviation. Wide usage of digital automatic systems in air traffic control and improvement of on-board equipment of airplanes reduced the number of accidents caused by mid-air collision. Introduced in 2003 Airborne Collision Avoidance System (ACAS) at the international level reduced the risk of mid-air collision significantly [3-4]. Currently, in a period of 2014-2018 years, only one accident with mid-air cause happened at international level [5]. But, rarely statistic of mid-air collisions does not reduce the significance of accidence, due to involving both airplanes and mostly resulting in catastrophe [5]. Currently, mid-air collision is an extremely rare event that even may not happen within investigated airspace volume and selected time frame. Thus, the risk of mid-air collision can not be assessed from frequency of this event occurrence. Therefore, in practice a probabilistic method of risk estimation is usually used.

Probabilistic methods of risk estimation usually based on estimating the probability of at least two airplanes locates closer at distance less than its geometrical dimensions. Risk value may be obtained from computer-based simulation of air traffic based on Monte Carlo method [6]. Simulation may take into account contribution of different factors that lead to specific causes, for example: air traffic conditions, onboard airplane equipment fault, navigation infrastructure [7], surveillance, human factor (concerning air traffic controller and pilot sides) [8], and weather conditions.

A Bayesian network and Information theory can be used to estimate the occurrence of mid-air collisions based on accident precursors. In this case influence of each factor is considered as fault tree which can lead to mid-air occurrence [9]. Also, many approaches are based on fault tree model, which considers influence of different factors on mid-air collision occurrence [10].

Other research is focused on simulation of collision risk based on free-flight concept [11]. In this case, each airspace user can use any possible trajectory within predefined space. Assumption of free routes space helps to simplify computer-based simulation, due to missing routes network, air traffic schedule, and flight plan database.

Some studies are based on the fact that two aircraft that are on the same level and fly in the same direction, have overlapping, or tendency to overlap, their longitudinal measurements from tiny to tend moment beginning and end of overlay. As there was an overlap of lateral measurements, it means that there is a possibility of collision of planes during the time of application. But, this study did not take into account the safety barriers that should prevent such situations. Such barriers include ACAS and air traffic controllers (ATC).

The chance of ACAS failure is quite small, but it exists and can be caused by the following factors:

- break transmitter prevents the transmission of any signals, including ACAS signal;
- breach or duplication of “mode S”, can result in unpredictable behavior of the system;
- breakdown or failure in mode C will lead to inaccurate (incomplete) ACAS operation.

ATC receives data from surveillance systems and based on them draws conclusions about the air situation and makes decisions on conflict resolution. However, in the human-technical relationship, the weak point is the person himself, because he has mistakes [12]. A person often makes mistakes in moments of greatest and least stress.

Therefore, a conflict situation that has arisen due to an ATC error is most likely when the workload on it is the largest or smallest.

The main objective of the research presented in this paper is to develop a model to estimate a risk of mid-air collision based on statistical analysis of prerecorded air traffic data within a defined volume of airspace. We propose an integrated approach for airspace performance estimation based on risk category of a mid-air collision. Obtained risk of a mid-air collision in the lateral plane is an important part of total airspace safety estimation.

2 Air traffic flow and separation

The conventional air traffic system is based on the number of flight routes. Air traffic can be only within defined routes developed and supported by the National air-navigation service provider [13]. All air navigation services are provided only within the network of routes.

At the flight planning stage, each airspace users have to prepare a flight plan and coordinate it with the flight data center. Flight plan considers airspace usage only within the network of routes. Once the flight plan is agreed, the aircraft must carry it exactly, because it is coordinated with the flight plans of other aircraft. Exact maintaining the cleared flight level and route is the key of aviation safety.

An air traffic flow is organized in compliance with the standards and recommended practices prescribed by aviation law [14]. These standards state that one of the main means of ensuring aviation safety is separation. Separation is a procedure that aims to create a distance or intervals between aircraft to ensure safety. There are three types of separation: vertical, horizontal (lateral), and longitudinal [14]. All types of separation have their minimum values depending on the phase of flight and the conditions under which they can be used.

Vertical separation is the creation of a vertical interval between aircraft, based on data obtained from radars and surveillance devices and their reduction into a single system of measurements. Therefore, all aircraft use the same parameters of the standard atmosphere to calculate altitude. Flight level (FL) is a predetermined altitude, which is calculated from the average sea level. The minimum vertical separation between aircraft is 300 m below 290 FL and 600 m for altitude of 290 FL and above [14].

Lateral separation is achieved by flying aircraft on different routes or being in different geographical locations. The minimum of lateral separation is based on means and methods of navigation. The width of the route is clearly prescribed by the air traffic authority. All data on the network of air routes and the structure of the airspace are registered in the collection of aeronautical information publication issued by the air traffic authority [13].

Minimums of Lateral separation utilize requirements of performance-based navigation (PBN) to on-board positioning system [15-16] and routes structure at a particular part of airspace. Thus, separation distance between airspace users on parallel or non-intersecting tracks depends on PBN specification type:

- RNAV 10 – 50 NM,
- RNP 4 – 23 NM,
- RNP 2 – 15 NM,
- RNP 2 (climbing or descending through the level of another airplane) – 7 NM,
- RNAV 1 – 7 NM,
- RNP 1 – 5 NM.

Longitudinal separation minimums are the following:

- RNP 4, 10 – 50 NM;
- RNP 2,4 – 30 NM [14].

Also, there are three basic types of routes:

- routes planned on an ongoing basis, they are part of strategic planning;
- routes in the unspecified scenario for specific tasks;
- routes of operational use only at the instruction of the ATC.

Longitudinal separation setups minimal interval between airplanes to ensure the required level of flight safety.

In addition to conventional Free Routes air traffic concept was integrated into many regions around the globe. Within a free routes area airspace, users can fill free to use any trajectory to fly. Safety levels support by high accuracy of navigation and surveillance systems.

3 Risk model of a mid-air collision

Each air space user can be represented as a thee- dimensional object in forms of sphere, ellipse, or box [17]. These shapes limit geometrical dimensions of particular airspace user or utilize separation minimums of particular airspace. The risk of mid-air collision can be represented as a probability of overlapping of two shapes within investigated airspace and defined traffic capacity. Spherical and ellipsoidal shapes are ideal for free routes tasks or collision avoidance based on risk value. For conventional air traffic, the most appropriate airplane model is a box with length λ_x, width λ_y, and height λ_z (see Fig. 1). Box size corresponds to a half of the separation minimums of investigated airspace. Due to requirements of maintaining separation minimums between airspace users. Any crossing of these boxes is considered as a mid-air collision according to reducing distance between airplanes in values less than required separation minimums.

Also, airspace user may be represented as a box with double size and all other airplanes as a single point for tasks of risk assessment. Thus, risk of separation lost is a probability of any airspace user occurrence in the double size box.

In case of box model a risk of mid-air collision can be estimated by Reich formula [17-18] which utilize probability of collision during a lateral overlap for airplanes in the same directions:

$$R = P_{xy} P_z \left(1 + \frac{\lambda_x v_y}{\lambda_y v_x} + \frac{\lambda_x v_z}{\lambda_z v_x} \right), \tag{1}$$

where P_{xy} is a probability of lateral overlap; P_z is a probability of vertical overlap; v_x, v_y, v_z are relative velocities by axes between airplanes.

Relative velocities depend on particular simulation case. For example, in the case of collision simulation at the en-route phase v_z=0. Values of v_x and v_y depend on particular conflict geometry in the lateral plane, and their calculation is based on mean relative velocity in a particular airspace.

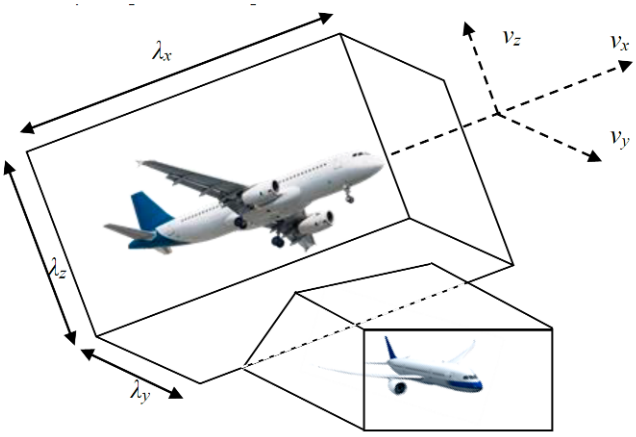

Fig. 1. The box model of airspace user

Probabilities of lateral and vertical overlaps are estimated based on the assumption of known probability density functions (PDF) of airplane deviation from cleared flight route centerline. Double Exponential Density Function [20], Laplacian, Normal Density Function, Exponential Density Function, Freshet, Weibull, Gumbel [17], Generalized Pareto Distribution can be used as PDF for tasks of risk assessment within air navigation system [21].

Parameters of PDFs are estimating based on statistical data processing of airplanes trajectories within a limited volume of airspace.

Airplane vertical deviations from cleared flight level are estimating with the help of precise radar. Results of altitude measurements along particular length of flight route are used for statistical data processing and PDF fitting to histogram of airplane deviations. Result of fitting gives parameters of PDF. For example, in the task of reduced separation minima selection, a mixture of two double exponential PDF was used [22-23]. Probability of vertical overlap P_z=0.48 is based on the research of North Atlantic Systems Planning Group for conventional air traffic system [19].

4 Probability of lateral overlap

Probability of lateral overlap may be estimated based on PDF of the relative lateral position of airspace users. In this case, probability is an area under PDF within the separation minimum (see Fig. 2).

Thus, probability can be estimated as follows:

$$P_{xy} = 1 - \int_{-\lambda_y}^{\lambda_y} \rho(y)dy\,, \tag{2}$$

where $\rho(y)$ is a PDF.

We use Triple Univariate Generalized Error Distribution (TUGED) function as PDF in the next form [21]:

$$\rho(y) = \alpha\rho_{NSE}(y) + \beta\rho_{FTE}(y) + (1 - \alpha - \beta)\rho_T(y)\,, \tag{3}$$

where $\rho_{NSE}(x)$ is the PDF utilizing the errors of navigation system; $\rho_{FTE}(x)$ is the PDF characterizing the *FTE*; $\rho_T(x)$ is the PDF characterizing the appearance of rare events; α and β are weight coefficients.

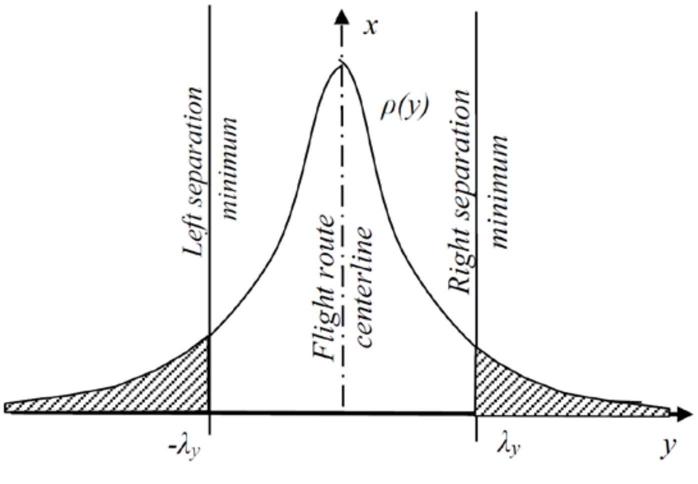

Fig. 2. PDF of airplane lateral deviation

Triple component of PDF provides the best fit of input statistical data due to taking into account two different levels of deviations connected with Navigation System Error (*NSE*) (or error of positioning system), Flight Technical Error (*FTE*) (or error of airplane maintaining at predefined route), and influence of rare events. In the case of manual control, FTE utilize influence of human factor.

In general form TUGED model can be represented by the following form [21]:

$$\begin{aligned}\rho(y) = {} & \frac{\alpha}{2a_1 b_1 \Gamma(b_1)} exp\left(-\left|\frac{y-b_1}{a_1}\right|^{b_1^{-1}}\right) + \frac{\beta}{2a_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{y-b_2}{a_2}\right|^{b_2^{-1}}\right) + \\ & + \frac{1-\alpha-\beta}{2a_3 b_3 \Gamma(b_3)} exp\left(-\left|\frac{y-b_3}{a_3}\right|^{b_3^{-1}}\right)\end{aligned} \tag{4}$$

where a_1,a_2,a_3 are of scale factors; b_1,b_2,b_3 are shape coefficients; μ_1, μ_2, μ_3 are mean values.

Sum of weight coefficients is limited by the following:

$$0 \le \alpha + \beta \le 1.$$

Scale and shape coefficients should follow:

$$1 \le a \le \infty;\ 0.5 \le b \le 1.$$

Let’s consider the case of equal probabilities of deviations in the left and right sides in order to improve computation performance:

$$\mu = \mu_1 = \mu_2 = \mu_3; \quad -\infty \le \mu \le \infty.$$

Weight, scale, and shape coefficients are estimated by statistics of airplane unplanned deviations from cleared trajectories by Maximum Likelihood Method [21].

5 Numerical demonstration

According to basic airspace rules, each user of controlled airspace has to be equipped with automatic dependent surveillance-broadcast (ADS-B) equipment. According to ADS-B regulation, each user has to share his own location with other airspace users.

Basic regulation required to use modified on-board air traffic control radar beacon system transponder with Mode “1090ES”. Transmitted data at 1090 MHz includes position reports from all airspace users around. These reports can be received by Software Defined Radio (SDR) and decoded by specific software (see Fig. 3).

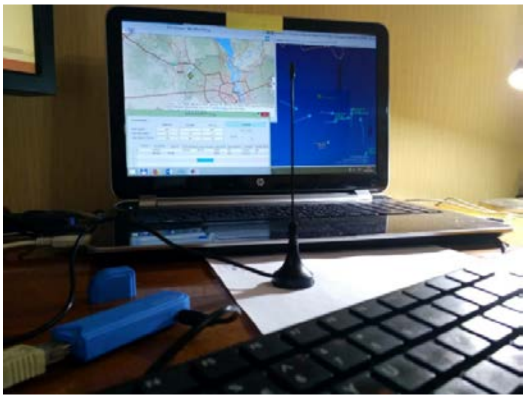

Fig. 3. SDR and software for data decoding

User location transmitted in Latitude, Longitude, and Altitude data format (WGS-84). Obtained via ADS-B “out” air traffic data is a result of on-board positioning which performs by Global Navigation Satellite System. Also, each transponder transmits a position report in the non-synchronized mode with different repeating frequency, which depends on transponder installation settings. One SDR gives an opportunity to receive position reports from numerous airspace users with the radius of maximal length of communication line which is approximately equal to 300NM for a Very High-Frequency spectrum. Thus, one SDR covers air traffic data within a circle of 300NM radius. A network of SDR can be used in order to get a data sample across the long territory.

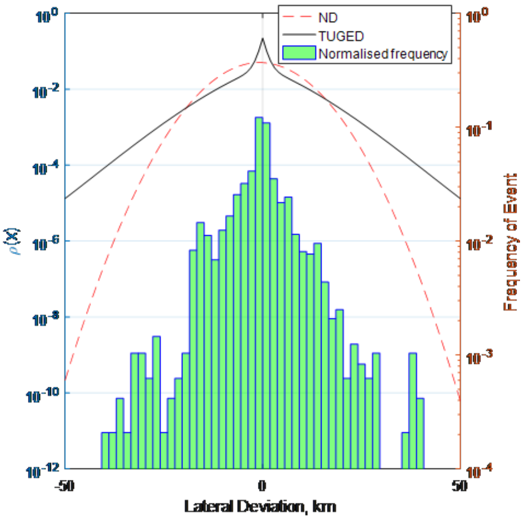

Fig. 4. Airplane deviations from the cleared trajectory in a lateral planewithin Ukrainian airspace

We use air traffic data recorded by SDR for 30 minutes on April 23, 2019. Statistical data processing of airplanes deviations from the Ukrainian routes network is provided based on digital database of flight routes and accumulated air traffic data from SDR. Obtained learning sample includes deviations of all air traffic, independently from the flight phase within investigated airspace volume (see Fig. 4).

Digital database of flight routes includes 331 waypoints within Ukrainian airspace. These waypoints are a connection points of direct flight routes. Our database includes 497 direct routes between two waypoints. Total length of investigated flight routes is 20840 NM for altitudes above 30000 ft. Detection of airspace users deviation from flight routes network is based on finding a minimal distance between airplane and each line of network.

A histogram of calculated deviations in the lateral plane accumulated for 30 minutes of input air traffic data is represented in Fig. 4. Amount of learning sample is 2723 measurements. We use bin width equal to 1 NM. The mean value is equal to -786 m and the standard deviation is 7924 m.

After fitting TUGED to input learning sample, parameters of $\rho(y)$ are estimated: α=0.59; β=0.03; μ=0; a_1=10.19; a_2=8.35 a_3=1; b_1=0.75; b_2=0.99; b_3=0.99.

Probability of lateral overlap estimated by (2) depends on model width λ_y related to air navigation specification and separation minimum. Distribution of P_{xy} is represented in Fig. 5.

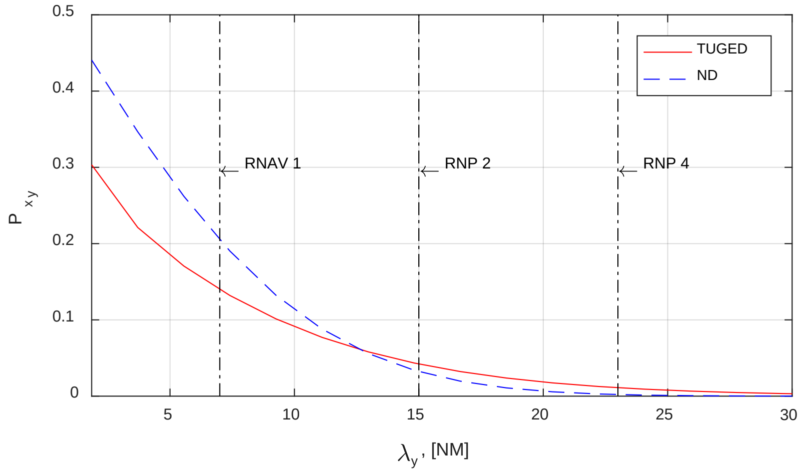

Fig. 5. Probability of lateral overlap

An input air traffic data sample gives us P_{xy}=0.13 for RNAV1 specification.

Then the risk of a mid-air collision in the lateral plane can be estimated by (1). The airplane model is used to satisfy RNAV 1 requirements valid below FL 290 (λ_x=12964m, λ_y=55560m, λ_z=300m). Due to study overall risk at an en-route phase of flight v_z=0 and considering the case of a collision with condition v_x=v_y than (1) can be represented in the following simplified form:

$$R = P_{xy} P_z \left(1 + \frac{\lambda_x}{\lambda_y} \right). \qquad (5)$$

Finally, risk of a mid-air collision in the lateral plane for air traffic data valid for Ukrainian airspace risk obtained by (5) is equal to 0.84 $\times 10^{-7}$.

6 Conclusion

In our study, we estimated the probability of mid-air collisions in lateral plane based on Reich equation and recorder by SDR air traffic data for Ukrainian airspace. Air space users' deviations in the lateral plane are estimated based on received user locations and national routes network.

Usage of TUGED at statistical analysis stage gives better performance than Double exponential or Normal PDFs due to taking into account flight technical error which is mostly utilized human factor influence based on input data.

Obtained value for risk of a mid-air collision in the lateral plane is higher in comparison with a risk value obtained for the Asian region [23] (7.41 × 10-8) due to usage of lateral separation minimums of RNAV 1 specification (7 NM) while for the study in the Asian region RNP 10 (50 NM) was used. Fig. 4 indicates the probability of lateral overlap in relation to model width (λ_y). Analysis of obtained data indicates that for bigger specification numbers the smaller value of probability of lateral overlap may occur. Thus, small risk value for Ukrainian airspace is a result of low traffic flow.

The results of this study can be used by controllers, pilots, and other air traffic participants for better flight planning and improving the structure of airspace in order to increase flight safety. The obtained results can be used to predict dangerous situations when flying on parallel routes and when creating lateral separation on routes.

References

1. Mid-air collisions. Safety study 1989-1999. Ministry of transportation and housing equipment - civil aviation security investigation and analysis office (2000).
2. Aviation Safety Reporting System. Database Online. NASA (2020). https://asrs.arc.nasa.gov/search/database.html
3. Overview of ACAS II. version 3.2. EUROCONTROL (2014).
4. Airborne Collision Avoidance System (ACAS) Manual. Doc 9863. ICAO (2006).
5. Safety Report 2018. International Air Transport Association. 55th edition. Geneva (2019).
6. Stroeve, S.H., Blom, H.A., Bakker, G.B.: Systemic accident risk assessment in air traffic by Monte Carlo simulation. Safety science 47(2): 238–249 (2009). DOI: 10.1016/j.ssci.2008.04.003
7. Ostroumov, I.V., Kuzmenko, N.S.: Risk Analysis of Positioning by Navigational Aids. In: Proc. of 2019 IEEE Int. Conf. Signal Processing Symposium (SPSympo-2019), pp. 92–95, Krakov (2019). DOI: 10.1109/SPS.2019.8882003

8. Henk, B., Bakker, B., Everdij, M., Van Der Park, M.: Collision risk modeling of air traffic. In: Proc. of 2003 IEEE Int. Conf. on European Control Conference, pp. 2236–2241, (2003). DOI: 10.23919/ecc.2003.7085299
9. Valdes, R.M., Liang Cheng, S.Z., Gomez Comendador, V.F., Saez Nieto, F.J.: Application of Bayesian networks and information theory to estimate the occurrence of mid-air collisions based on accident precursors. Entropy 20(12): 1–19 (2018). DOI: 10.3390/e20120969
10. Blom, H., Krystul, J., Bakker, G., Klompstra, M., Obbink, B.: Free flight collision risk estimation by sequential MC simulation. Stochastic hybrid systems: 249–281 (2007).
11. Shepherd, R., Cassell, R., Thapa, R., Lee, D.: A reduced aircraft separation risk assessment model. In: Proc. of 1997 AIAA International Conference on Guidance, Navigation, and Control Conference, pp.1–16, New Orleans (1997).
12. Rizun, N., Shmelova, T.: Decision-making models of the human-operator as an element of the socio-technical systems. Strategic imperatives and core competencies in the era of robotics and artificial intelligence: 167–204 (2016). DOI:10.4018/978-1-5225-1656-9.ch009
13. Aeronautical Information Publication (AIP) of Ukraine. Ukrainian State Air Traffic Services Enterprise. (2020).
14. Air traffic management, Procedures for Air Navigation Services. Doc. 4444. ICAO (2016).
15. Ostroumov, I.V., Kuzmenko, N.S.: An area navigation RNAV system performance monitoring and alerting. In: Proc. of 2018 IEEE Int. Conf. on System Analysis & Intelligent Computing (SAIC 2018), pp. 211–214, Kyiv (2018). DOI:10.1109/SAIC.2018.8516750
16. Ostroumov, I.V., Kuzmenko, N.S.: Accuracy improvement of VOR/VOR navigation with angle extrapolation by linear regression. Telecommunications and Radio Engineering 78(15): 1399–1412 (2019). DOI:10.1615/TelecomRadEng.v78.i15.90
17. A Unified Framework for Collision Risk Modelling in Support of the Manual on Airspace Planning Methodology for the Determination of Separation Minima. Doc. 9689. ICAO (2009).
18. Reich, P.G.: Analysis of Long-range Air Traffic Systems: Separation Standards. Journal of the Institute of Navigation 19: 88–98 (1966). DOI: 10.1017/S037346330004056X
19. Brooker, P.: Longitudinal collision risk for ATC track systems: a hazardous event model. The Journal of Navigation 59(1): 55–70 (2006). DOI: 10.1017/S0373463305003516
20. Ryota, M.: Identifying the ratio of aircraft applying SLOP by statistical modeling of lateral deviation. Transactions of the Japan Society for Aeronautical and Space Sciences 54(183): 30–36 (2011). DOI: 10.2322/tjsass.54.30
21. Ostroumov, I.V., Marais, K., Kuzmenko, N.S., Fala, N.: Triple Probability Density Distribution model in the task of Aviation Risk Assessment. Aviation 24(2): 57–65 (2020). DOI: 10.3846/aviation.2020.12544
22. Review of The General Concept of Separation Panel – Sixth Meeting, Doc. 9536, RGCSP/6, Vol. 1. ICAO (1988).
23. The 17th Meeting of the Regional Airspace Safety Monitoring Advisory Group. RASMAG/17−WP07. International Civil Aviation Organization. Bangkok, Thailand (2012).