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Assessment of Flight Safety in the Area Navigation Route System using the ATS Surveillance Information

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Abstract

This article describes the approach of Russian specialists to the calculation of technical and total collision risks when evaluating flight safety on area navigation routes with RNAV 1, RNAV 2 and RNAV 5 specifications. The Russian approach is based on the analysis and processing of discrete air traffic services surveillance information. Two scenarios are used for processing discrete information from the surveillance system as related both to the flight paths of individual aircraft (scenario a)) and to all aircraft operated (scenario b)).

The processing according to scenario a) makes it possible to assess the actual characteristics of the aircraft accuracy of maintaining the assigned tracks of the flight routes and the actual characteristics of the accuracy of displaying the aircraft coordinates on the controller's air situation display.

The processing under scenario b) allows fixing actual situations of simultaneous violation of the minimum vertical separation interval and aircraft proximity in the horizontal plane to intervals close to the minimum safe one $S_{\min} : 0 < S \le 2 \cdot S_{\min}$.

The acceptable (target) level of safety of technical and total collision risks is substantiated for solving the tasks of the aircraft separation using the information of the surveillance system. The formulas for calculating the technical and total collision risks are presented, and various decision options are substantiated based on the results of comparing the target risk values with the corresponding safety level estimates.

The developed approach can be used to monitor the flight safety in the horizontal plane by processing the actual information of the aircraft movement surveillance.

Keywords: target level of safety, technical, overall collision risk, monitoring, aircraft, flight safety.

INTRODUCTION

The need to assess the safety of aircraft operations on newly established area navigation routes with RNAV specifications, with the availability of ATS surveillance system information, is defined in international and Russian regulatory documents [1, 2].

The Russian approach to assessment of aircraft (A/C) flight safety with RNAV 1, RNAV 2 and/or RNAV 5 specifications is based on the analysis of discrete air traffic surveillance information, which is an integral part of the air traffic services system of the corresponding area of responsibility.

Two scenarios are used for processing the discrete information of the ATS surveillance system:

a) extracting the discrete coordinate information relating to flight paths of individual aircraft from the general data set and its processing;

b) processingthe discrete measurements of the coordinates of all possible aircraft currently under surveillance, with a view to calculating vertical and horizontal intervals between them.

MATERIALS AND METHODS

Major objectives in discrete coordinate information processing under scenario a)

The discrete information on the path in scenario a) is used mainly to obtain continuous paths of all aircraft flights along the investigated routes. The continuous 3D flight path of the aircraft is obtained parametrically by processing the discrete 3D path information $\{\varphi(t_i), \lambda(t_i), h(t_i)\}_{i=1}^{N}$.Aircraft coordinates in the horizontal plane $\{\varphi(t_i), \lambda(t_i)\}_{i=1}^{N}$ are smoothed by natural cubic splines $S_{3,\varphi}(t)$ and $S_{3,\lambda}(t)$ constructed by the ordinary least squares method (OLS splines). The aircraft ground speed is also obtained by smoothing the array of indirect discrete measurements $\{W(t_i)\}_{i=1}^{N}$ by a natural cubic OLS spline $S_{3,W}(t)$.

The continuous flight path of the aircraft in the vertical plane is obtained by smoothing the discrete measurements

$\{h(t_i)\}_{i=1}^{N}$ by a natural linear OLS spline $S_{1,h}(t)$. The vertical velocity of the aircraft is obtained by smoothing the array of indirect measurements $\{h'(t_i)\}_{i=1}^{N}$ by a natural linear OLS spline $S_{1,\dot{h}}(t)$.

The joint processing of the discrete flight path of the aircraft in the horizontal plane $\{\varphi(t_i),\lambda(t_i)\}_{i=1}^{N}$ and the continuous path $(S_{3,\varphi}(t),\, S_{3,\lambda}(t))$ derived from it makes it possible to assess the standard deviation of the linear accuracy in determining the coordinates of the aircraft by the surveillance system (σ_l).The spline approximation of discrete data is performed on the basis of the classical approach for constructing spline functions, as that described, for example, in [3-7].

The joint processing of the continuous flight path($S_{3,\varphi}(t),\, S_{3,\lambda}(t)$)and the specified track of a specific area navigation route $(\varphi_{RNAV_k}(t),\lambda_{RNAV_k}(t))$ enables assessment of the navigation performancefor both the specific flight of the aircraft and, as a whole, for the totality of the performed flights on the ktharea navigation route for the monitoring period: $L_{y_k}^{0.95}$; $L_{x_k}^{0.95}$.

The additional analysis of the discrete path information of the surveillance system under scenario a) provides for the assessment of the following parameters:

- flying time for a separate flight of the aircraft and the totality of the performed flights along the area navigation routes;
- interval of updating the measurements of the coordinate information from the surveillance system;
- probability of an absent missed measurement of the coordinate information of the aircraft;
- probability of missing the measurement of the coordinate information on the aircraft position provided that the previous measurement of the coordinate information is also missed, and other actual characteristics of the ATS surveillance system information.

2.2. Major objectives in discrete coordinate information processing under scenario b)

The discrete coordinate information of all possible aircraft currently under surveillance (scenario b)) makes it possible to determine possible situations of simultaneous violation of horizontal and vertical minimum separation intervals between aircraft flying along area navigation routes. At the same time, unlike the algorithm of alerting the controller about dangerous aircraft proximity, which should detect situations of simultaneous violations of horizontal and vertical intervals in the traffic forecast, thecollision risk monitoring requires using only the current coordinates of the aircraft 3D position measurements on the area navigation routes.

Assume that at some current time N aircraft areunder surveillance. It is necessary to analyze the horizontal and vertical intervals $C_N^2 = \dfrac{N\cdot(N-1)}{2}$ of various aircraft pairs. For each of the C_N^2 pairs, calculate the vertical interval S_z as the altitude difference in the 3D discrete information of the aircraft under consideration:

$S_z = h_A - h_B$, where A and B are conditional aircraft of the pair under consideration.

If

$$S_z \le 1000[ft] + \Delta H, \qquad (1)$$

then a horizontal interval is calculated for this aircraft pair: $S_{xy} = f(\varphi_A,\lambda_A,\varphi_B,\lambda_B)$.

Otherwise, proceed to another aircraft pair, calculate the vertical interval and compare it with the value $1000[ft] + \Delta H$.

If

$$S_{xy} \le S_{\min} + \Delta S_{xy}, \qquad (2)$$

then the intervals for the given aircraft pair need be more carefully evaluated for checking simultaneous violation of the minimum horizontal and vertical intervals.

The values ΔH and ΔS_{xy} depend on the accuracy of the pressure (barometric) altitude (σ_h) measurements and the linear accuracy of measuring the horizontal coordinates of the aircraft (σ_l). In the first approximation we have:

$$\Delta H = 2\cdot\sqrt{2}\cdot\sigma_h;$$

$$\Delta S_{xy} = 2\cdot\sqrt{2}\cdot\sigma_l,$$

where:

σ_h – is accuracy of the discrete information on the aircraft pressure altitude in the 3D coordinate information of the surveillance system;

σ_l – is linear accuracy of measuring aircraft horizontal coordinates in the 3D coordinate information of the surveillance system.

Safety assessment for the calendar period of risk

monitoring

Preparation for collision risk assessment :

Assume that conditions (1) and (2) aremet simultaneously for some aircraft pair. Regarding this pair, it is necessary to determine with the greatest possible certainty whether there has been a simultaneous violation of the established minimum intervals or not. To solve the problem, it is necessary to reconstruct the continuous 3D flight paths of the aircraft from the considered pair, to assess the continuous relative distances in the horizontal and vertical planes $\left(S_{xy}(t), S_z(t)\right)$and to determine the presence of a simultaneous violation of the established minimum intervals $S_{\min}$ and $1000[ft]$, and the time interval of this violation(t_{0_j} , t_{1_j})for the indicated jth pair in the time interval(t_{0_j} , t_{1_j}); also the minimum value is determined:

$S_{xy_{\min}}(t_{\min\_j})$ and $S_z(t_{\min\_j})$,

where:

$t_{\min_j} \in (t_{0_j}, t_{1_j})$;

$S_{xy_{\min}}(t_{\min\_j}) < S_{\min}$;

$S_z(t_{\min\_j}) < 1000[ft]$.

As a result of these actions, an array of data can be generatedfor a calendar period

$$\left\{S_{xy_{\min\_j}}, S_z(t_{\min\_j})\right\}_{j=1}^{R}. \quad (3)$$

For the completeness of the safety assessment for flights along the area navigation routes in the analysis of discrete 3D coordinates of all possible aircraft, in addition to the simultaneous fulfillment of criteria (1) and (2), it is necessary to verify the fulfillment of criterion (1) together with condition

$$S_{\min} + \Delta S_{xy} \le S_{xy} \le 2 \cdot S_{\min} + \Delta S_{xy}. \quad (4)$$

For each aircraft pair for which the criteria (1) and (4) are met simultaneously, all procedures must be performed that are assumed for an aircraft pair with simultaneous criteria (1) and (2).

As a result of these actions, an array of data must be generated for a calendar period

$$\left\{S_{xy_{\min\_i}}, S_z(t_{\min\_i})\right\}_{i=1}^{M}. \quad (5)$$

where:

$S_{\min} \le \Delta S_{xy_{\min}} \le 2 \cdot S_{\min}$;

$S_z(t_{\min\_i}) < 1000[ft]$.

In addition, for the same calendar period, the total volume of aircraft operations along the area navigation routes with RNAV 1, RNAV 2 and/or RNAV 5 specifications should be evaluated based on the processing of the surveillance system discrete information under scenario a): T_Σ.

Note, that a continuous flight path of the aircraft from the discrete coordinate information containing measurement errors is obtained on the basis of solving a special mathematical problem and is not provided in this paper. Its full description is given in [8, 9].

Target level of aircraft flight safety along area navigation routes with RNAV 1 and/or RNAV 5 specifications

At present, the ICAO and states (groups of states) with well-developed aviation industries considers the value of $15.0 \times 10^{-9} \frac{1}{fl.hour}$ for the target level of safety (TLS) as an acceptable valuefor three types of separation with equal partition by separation types [10-14].

The aircraft separation during flights along area navigation routes refers to its longitudinal type; therefore, in the Russian Federation, the TLS of the total collision risk when flying along area navigation routes is accepted as $5.0 \times 10^{-9} \frac{1}{fl.hour}$:

$$TLS_{RNAV}^{total} = 5.0 \times 10^{-9} \frac{1}{fl.hour}.$$

By analogy with the TLS for vertical separation, here one should single out a target level of flight safetyfrom the total risk, which depends only on technical reasons: navigation errors, surveillance and configuration of area navigation routes. In the Russian Federation, the value of the target technical risk is accepted as $5.0 \times 10^{-10} \frac{1}{fl.hour}$:

$$TLS_{RNAV}^{tech} = 5.0 \times 10^{-10} \frac{1}{fl.hour}.$$

If there are violations of the separation intervals due to ATC controller/pilot'serrors, ground/airborne failures or airbornecontingent situations, then the technical risk grades into the total risk.

Assessment of the technical collision risk along the area navigation routes during the safety monitoring period

Assume thatsome data array (5) isgenerated at the stage of preparation for the assessment of technical risk for the established calendar period:

$$\left\{S_{xy\,\min\_i} S_z(t_{\min\_i})\right\}_{i=1}^{M}.$$

In addition, for the same calendar period, the value T_Σ and linear accuracy of the aircraft coordinates determination by the surveillance system σ_l were evaluated.

The technical risk is evaluated by the following formula:

$$N_{a\Sigma\_RNAV}^{tech} = \frac{2\times\sum_{i=1}^{M} HOP(S_{xy_{\min\_i}})\cdot P_z(S_z(t_{\min\_i}))}{T_\Sigma}, \quad (6)$$

where:

$HOP(S_{xy_{\min\_i}}) = 2\cdot T\cdot C_{xy}(S_{xy_{\min\_i}})$ – is the probability of aircraft horizontal overlap;

T – is the diameter of the cylinder approximating the average horizontal dimension of the aircraft flying along the area navigation routes;

$C_{xy}(S_{xy_{\min\_i}})$ – is the density of the probability of the aircraft horizontal overlap with the observed distance between them equal to $S_{xy_{\min\_i}}$.

The technical risk assessment uses the Eurocontrol approach described in [15-17]. Previously, the same approach was used in the so-called CAP method (P_{CA}) [18-20]. For each $S_{xy_{\min\_i}}$ value, the $C_{xy}(S_{xy_{\min\_i}})$ value is chosen in accordance with [21];

$P_z(S_z(t_{\min\_i})) = 2\cdot\lambda_z\cdot C_z(S_z(t_{\min\_i}))$ – is the probability of vertical overlap for the ithaircraft pair with a measured vertical separation equal to $S_z(t_{\min\_i})$

$$C_z(S_z(t_{\min\_i})) = \int_{-\infty}^{\infty} f_z(z)\cdot f_z(z - S_z(t_{\min\_i}))dz;$$

$f_z(z)$ – is the density of the probability of the total error inmaintaining the given altitude.

In [15] the following robust value of the vertical overlap probability is used:

$$P_z(S_z(t_{\min\_i})) = \begin{cases} 0.4, \text{ if both aircraft are on the same flight level;} \\ 0.11, \text{ if one aircraft is on the flight level, and the other one changes} \\ \text{its altitude within the range of } \pm 500 \text{ ft maximum} \end{cases}$$

Assessment of the total collision risk along the area navigation routes during the safety monitoring period

Assume that data sets (3) and (5) are generated at the stage of preparation for the assessment of the total risk for the established calendar period:

$$\left\{S_{xy\,\min\_j}, S_{z\,\min\_j}\right\}_{j=1}^{R};$$

$$\left\{S_{xy\,\min\_i}, S_z(t_{\min\_i})\right\}_{i=1}^{M}.$$

The total risk is evaluated by the following formula

$$N_{a\Sigma\_RNAV}^{total} = \frac{2\times\left[\sum_{i=1}^{M} HOP(S_{xy_{\min\_i}})\cdot P_z(S_z(t_{\min\_i})) + \sum_{j=1}^{K} HOP(S_{xy_{\min\_j}})\cdot P_z(S_z(t_{\min\_j}))\right]}{T_\Sigma}. \quad (7)$$

All explanations regarding the values of $HOP(\ldots)$ and $P_z(\ldots)$ given in clause 3.3, are valid in assessing the totalcollision risk taking into account violations of the minimum horizontal separation intervals.

RESULTS AND DISCUSSION

The decision on achieving the objectives of area navigation implementation in terms of ensuring flight safety based on the analysis of technical $\left(N_{a\Sigma\_RNAV}^{tech}\right)$ and total $\left(N_{a\Sigma\_RNAV}^{total}\right)$ collision risk assessments for a calendar period depends on the formulation of these objectives.

Assuming that safety objectives imply the simultaneous satisfaction of the following inequalities:

$$N_{a\Sigma\_RNAV}^{tech} \le TLS_{RNAV}^{tech};$$

$$N_{a\Sigma\_RNAV}^{total} \le TLS_{RNAV}^{total},$$

there are four solutions:

a) if

$$N_{a\Sigma\_RNAV}^{tech} \le TLS_{RNAV}^{tech}$$

$$and$$

$$N_{a\Sigma\_RNAV}^{total} \le TLS_{RNAV}^{total},$$

then the safety objectives for the calendar period have been achieved;

b) if

$$N_{a\Sigma\_RNAV}^{tech} > TLS_{RNAV}^{tech}$$

and

$$N_{a\Sigma\_RNAV}^{total} \le TLS_{RNAV}^{total} ,$$

then one of the objectives (the first one) has not been achieved. The most probable reason for this is the insufficient accuracy of the 3D coordinate information of the ATS radar surveillance system. It is necessary to develop and implement an Action plan to improve the parameters of the ATS surveillance system in the ATM area of responsibility under consideration;

c) if

$$N_{a\Sigma\_RNAV}^{tech} \le TLS_{RNAV}^{tech}$$

and

$$N_{a\Sigma\_RNAV}^{total} > TLS_{RNAV}^{total} ,$$

then one of the objectives (the second one) has not been achieved. The most probable cause of this areair traffic controllers and aircraft crews'excessive errors leading to an unacceptable rate of violations of the minimum horizontal and vertical intervals for the calendar period.

It is necessary to develop and implement an Action plan for additional training ofcontrollers and additional training of aircraft crews. It is necessary to analyze the area navigation routes and, if necessary, re-structure them. It is necessary to change the algorithms for airspace planning and aircraft flow arrangement;

d) if

$$N_{a\Sigma\_RNAV}^{tech} > TLS_{RNAV}^{tech}$$

and

$$N_{a\Sigma\_RNAV}^{total} > TLS_{RNAV}^{total} ,$$

then the safety objectives have not been achieved. Complex measures are required to change the ATM of the area, which are partially described in points b) and c).

CONCLUSION

This paper describes special algorithms for processing discrete coordinate information of operating air traffic control systems, the area of responsibility of which includes area navigation routes,whichmake it possible toassess the technical and total collision risks and compare their values with target flight safety levels.

In general, the approach presented can be used in monitoring aircraft safety in the horizontal plane provided that actual 3D discrete coordinate information from the ATS surveillance system is available for thesespecial algorithms.

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