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Selection of the Error Density for Measuring Aircraft Coordinates in the ATS Surveillance System to Assess the Safety of Flights along Area Navigation Routes

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Abstract

The approach is based on a comparison of the values of the aircraft overlap probabilities density in the horizontal plane for the selected values of the observed separations, which are convolutions of the probability densities for linear errors in measuring A/C coordinates using reference radars. The comparison covered error probability densities recommended by ICAO and applied in the USA (G_G), recommended by Eurocontrol and used in the United Kingdom (DE_DE), as well as two probability densities “spiritually” close to them: G and DE. The probability of the actual aircraft overlap in the horizontal plane was calculated, with the observed aircraft separation equal to $S\ (HOP(S))$. As a criterion for choosing an analytic expression for the error density, we used the maximum probability value $HOP(S)$, which depends on the form of the density with same value. It is shown that neither the ICAO model (USA) G_G, nor the Eurocontrol model (UK) DE_DE, nor alternative models of error densities G and DE do not have a guaranteed advantage against each other by the criterion of the maximum value of $HOP(S)$ for the S values used in the flight safety assessment. The proposed solution to the problem of choosing an analytic expression for the probability density of radar linear errors has scientific novelty of the universal importance.

Keywords: reference radar, error probability density, flight safety, aircraft, azimuth errors.

INTRODUCTION

In studies related to flight safety involving aircraft separation and the use of the ATS surveillance system information, the Russian Federation and the foreign ICAO states with well-developed aviation industries have accumulated a positive experience in describing the linear errors in the measurement of aircraft coordinates to assess the aircraft collision risk for the observed distances not less than the separation minimum. However, there are practical problems in assessing the flight safety when aircraft are converging at distances smaller than the allowed minimum.

The present paper is describes the choice of an analytical expression for the probability density of linear errors with known values of the mean square errors of the ATS surveillance system information.

MATERIALS AND METHODS

Existing models of azimuth herrors in aircraft coordinates measurements made by the reference radar

In addition to other functions, the air traffic services (ATS) surveillance system is designed to measure the aircraft coordinates. Unfortunately, any system measures coordinates with errors. The errors of the secondary surveillance monopulse radar are sufficiently well studied and described as models of azimuth errors of the so-called reference radar.

Currently, two models are used to describe the errors of the target azimuth measurement in safety assessment:

the ICAO model [1];

the Eurocontrol model [2].

The ICAO model describes azimuth errors in measuring the aircraft azimuth as a mixture of normal (Gaussian (G)) distributions with the following density:

$$f_{aG\_G}(a) = (1-\alpha)\cdot G(a;\sigma_{a1}) + \alpha \cdot G(a;\sigma_{a2}), \qquad (1)$$

where:

$$G(a;\sigma_a) = \frac{1}{\sqrt{2\pi}\sigma_a}\cdot e^{-\frac{a^2}{2\sigma_a^2}};$$

σ_a^2 is the azimuth error variance;

α is the mixture weight;

$\sigma_{a2} = 5\cdot\sigma_{a1}\ [\deg]$;

$\alpha = 0.05$;

$\sigma_{a1} = 0.054\,[\deg]$;

$\sigma_{a2} = 0.27\,[\deg]$.

The Eurocontrol model describes azimuth errors in measuring the aircraft azimuth as a mixture of two-sided exponential (DE) distributions with the following density:

$$f_{a\,DE\_DE}(a) = (1-\beta)\cdot DE(a;p_a) + \beta\cdot DE(a;q_a), \quad (2)$$

where:

$$DE(a;\lambda) = \frac{1}{2\lambda}\cdot e^{-\frac{|a|}{\lambda}};$$

$\lambda^2\left(p_a^2, q_a^2\right)$ is the parameter of azimuth error dispersion for DE distribution;

β is the mixture weight;

$q_a = \frac{10}{3}\cdot p_a\,[\deg]$;

$\beta = 0.008$;

$p_a = 0.036\,[\deg]$;

$q_a = 0.120\,[\deg]$.

The dispersion of the reference radar azimuth errors with density (1) is defined as:

$$D_{aG\_G} = (1-\alpha)\cdot\sigma_{a1}^2 + \alpha\cdot 25\cdot\sigma_{a1}^2.$$

It is plain that the standard deviation (RMS) of the azimuth errors will be equal to

$$\sigma_{aG\_G} = \sigma_{a1}\cdot\sqrt{1+24\cdot\alpha} = 0.0801\,[\deg]. \quad (3)$$

The dispersion of the reference radar azimuth errors with density (2) is defined as

$$D_{a\,DE\_DE} = \frac{2}{9}\cdot p_a^2\cdot(9+91\beta).$$

It is plain that the standard deviation of the Eurocontrol reference radar azimuth errors will be equal to

$$\sigma_{a\,DE\_DE} = \frac{p_a}{3}\cdot\sqrt{2\cdot(9+91\beta)} = 0.0529\,[\deg]. \quad (4)$$

The linear RMS value of the aircraft coordinate error isrelated with the azimuth RMS value for errors in the coordinate measurement by a known relation [3-6]:

$$\sigma_l = \sigma_a\cdot\frac{\pi}{180}\cdot R, \quad (5)$$

where R – is the range between the aircraft and the reference radar.

It can be shown that there are definite relations between the linear RMS values for errors in determining the aircraft coordinates and the azimuth RMSs.

For model (1), these relations are as follows:

$$\left.\begin{aligned} \sigma_{l\,G\_G} &= \sigma_{l1}\cdot\sqrt{1+24\alpha}\,[m]; \\ \sigma_{l1} &= \frac{\sigma_{l\,G\_G}}{\sqrt{1+24\alpha}}\,[m]; \\ \sigma_{l2} &= 5\cdot\sigma_{l1}. \end{aligned}\right\} \quad (6)$$

For model (2) these relations are:

$$\left.\begin{aligned} \sigma_{l\,DE\_DE} &= \frac{p_l}{\sqrt{3}}\sigma_{l1}\cdot\sqrt{2(9+91\beta)}\,[m]; \\ p_l &= \frac{3\cdot\sigma_{l\,DE\_DE}}{\sqrt{2(9+91\beta)}}\,[m]; \\ q_l &= \frac{10\cdot\sigma_{l\,DE\_DE}}{\sqrt{2(9+91\beta)}}\,[m]. \end{aligned}\right\} \quad (7)$$

New problems in assessing the flight safety based on radar surveillance system information

Recall that the models of azimuth errors in the measurement of the aircraft position made by the reference radar (1) and (2) were introduced to solve specific problems of safety assessment when monitoring a linear safe horizontal interval between aircraft not less than $S_{\min}$ using the coordinate information from the reference radar (CAP, $SSEP$) [7-11].

However, the monitoring of flight safety along area navigation routes with RNAV 1 and/or RNAV 5 specifications offers new problems related to both the safety assessment at intervals close to the minimum safe interval $S_{\min}$ ($S_{\min} \le S \le 2\cdot S_{\min}$) and the safety assessment when violations of minimum horizontal separation intervals ($0 < S < S_{\min}$) take place [12].

For these problems, we will assess flight safety by comparing the collision risk assessment in the system of area navigation routes under consideration for a calendar period of time with an acceptable (target) risk value (TLS). To assess the collision risk, we will use the Eurocontrol approach based on assessments of the horizontal overlap probability (HOP) for anaircraft pair [2, 13, 14]:

$$HOP_j = 2 \cdot T \cdot C(S_j) \ , \tag{8}$$

where:

T is the diameter of the base of the averaged circular cylinder approximating the aircraft on the considered area navigation routes for a calendar period of time;

S_j is the minimum approach interval for the j-th aircraft pair registered along the area navigation routes for the calendar period of the safety monitoring. It is plain that for all S_j the following condition should be met:

$$0 < S_j \le 2 \cdot S_{\min} \ ; \tag{9}$$

$C(S_j)$ is the density of the overlapping probability forthe aircraft pair in the horizontal plane with the observed distance between them equal to S_j:

$$C(S_j) = \int_{-\infty}^{\infty} f_l(y) \cdot f_l(y - S_j) dy \ [2] \equiv (\text{for symmetric functions} \quad f_l(y)) \equiv$$
$$\equiv \int_{-\infty}^{\infty} f_l(y) \cdot f_l(S_j - y) dy \, [15]; \tag{10}$$

$f_l(y)$ is the density of probability of linear errors in determining the aircraft coordinate. It is plain that the $C(S_j)$ value depends essentially on the type of $f_l(y)$ densities and on the $0 < S_j \le 2 \cdot S_{\min}$ value.

Let us introduce the following rule for choosing an analytic expression of the probability density for errors in determining the aircraft coordinates. To assess flight safety in the area navigation route system with RNAV 1, RNAV 2 and/or RNAV 5 specifications, we will use such an analytical type of the probability density of errors in determining the aircraft coordinates usingthe reference radar, in which (other things being equal) the $C(S_j)$ value is the maximum for all the types of densities under test.

Let uscomplement models (1) and (2) of the reference radarazimuth errors, which are mixtures of Gaussian (G_G) and two-sided exponential (DE_DE) densities, with a simple Gaussian (G) and simple two-sided exponential (DE) density of the reference radars:

$$f_{a\,G}(a) = \frac{1}{\sqrt{2\pi}\sigma_{a\,G}} \cdot e^{-\frac{a^2}{2 \cdot \sigma_{a\,G}}} \ , \tag{11}$$

where $\sigma_{aG} = \sigma_{aG\_G} = 0.0801\,[\text{deg}]$;

σ_{lG} is a linear RMS value (determined in (5));

$$f_{a\,DE}(a) = \frac{1}{2 \cdot \lambda_{a\,DE}} \cdot e^{-\frac{|a|}{\lambda_{a\,DE}}} \ , \tag{12}$$

where $\sigma_{a\,DE} = \sqrt{2} \cdot \lambda_{a\,DE} = 0.0801\,[\text{deg}]$.

$$\lambda_{l\,DE} = \frac{\sigma_{l\,DE}}{\sqrt{2}} \ [km].$$

In accordance with the rule introduced, we select the analytic density of their four specific densities having the densities of azimuth errors (1), (2), (11) and (12). Since the selection criterion is the maximum value of the aircraft overlap probability at the observed S value, the probability density for the azimuth errors should be rewritten in their equivalents for linear errors in determining the coordinates of an individual aircraft. We obtain:

$$f_{l\,G\_G}(y) = (1-\alpha) \cdot \frac{1}{\sqrt{2\pi}\sigma_{l1}} \cdot e^{-\frac{y^2}{2 \cdot \sigma_{l1}^2}} + \alpha \cdot \frac{1}{\sqrt{2\pi}\sigma_{l\,2}} \cdot e^{-\frac{y^2}{2 \cdot \sigma_{l\,2}^2}} ; \tag{13}$$

$\alpha = 0.05;$

$$\sigma_{l1} = \frac{\sigma_{l\,G\_G}}{\sqrt{1 + 24 \cdot \alpha}};$$

$\sigma_{l\,2} = 5 \cdot \sigma_{l\,1}$;

$$f_{l\,DE\_DE}(y) = (1-\beta) \cdot \frac{1}{2 \cdot p_l} \cdot e^{-\frac{|y|}{p_l}} + \beta \cdot \frac{1}{2 \cdot q_l} \cdot e^{-\frac{|y|}{q_l}} ; \tag{14}$$

$\beta = 0.008;$

$$p_l = \frac{3 \cdot \sigma_{l\,DE\_DE}}{\sqrt{2(9 + 91 \cdot \beta)}};$$

$$q_l = \frac{10}{3} \cdot p_l \ ;$$

$$f_{l\,G}(y) = \frac{1}{\sqrt{2\pi}\sigma_l} \cdot e^{-\frac{y^2}{2 \cdot \sigma_l^2}} ; \tag{15}$$

$\sigma_l = \sigma_{l\,G}$;

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$$f_{l\,DE}(y) = \frac{1}{2 \cdot \lambda_l} \cdot e^{-\frac{|y|}{\lambda_l}}; \tag{16}$$

$$\lambda_l = \frac{\sigma_{l\,DE}}{\sqrt{2}}$$

In [16], D.A. Hsu showed that the density (16) is an infinite mixture of Gaussian densities with various dispersions having an exponential probability density with the “variance” parameter equal to $2 \cdot \lambda_l^2$. Thus, all types of considered types of densities of linear errors in determining the aircraft coordinates (13), (14), (15) and (16) using the reference radar are more or less related to normal errors[17, 18].

For the abovementioned error densities, the aircraft overlap probability densities will, respectively, be equal to:

$$C_{G\_G}(S) = \frac{(1-\alpha)^2}{\sqrt{2\pi} \cdot \left(\sigma_{l1}^2 + \sigma_{l1}^2\right)^{\frac{1}{2}}} \cdot e^{-\frac{S^2}{2\cdot\left(\sigma_{l1}^2+\sigma_{l1}^2\right)}} + \frac{2 \cdot (1-\alpha) \cdot \alpha}{\sqrt{2\pi} \cdot \left(\sigma_{l1}^2 + \sigma_{l2}^2\right)^{\frac{1}{2}}} \cdot e^{-\frac{S^2}{2\cdot\left(\sigma_{l1}^2+\sigma_{l2}^2\right)}} + \tag{17}$$

$$+ \frac{\alpha^2}{\sqrt{2\pi} \cdot \left(\sigma_{l2}^2 + \sigma_{l2}^2\right)^{\frac{1}{2}}} \cdot e^{-\frac{S^2}{2\cdot\left(\sigma_{l2}^2+\sigma_{l2}^2\right)}};$$

$$\begin{aligned} C_{DE\_DE}(S) = {} & \left(\frac{(1-\beta)}{2 \cdot p_l}\right)^2 \cdot \left(|S| + p_l\right) \cdot e^{-\frac{|S|}{p_l}} + \\ & + \frac{\beta(1-\beta)}{2}\left[\frac{1}{q_l - p_l} \cdot \left(e^{-\frac{|S|}{q_l}} - e^{-\frac{|S|}{p_l}}\right) + \frac{1}{q_l + p_l} \cdot \left(e^{-\frac{|S|}{q_l}} + e^{-\frac{|S|}{p_l}}\right)\right] + \\ & + \left(\frac{\beta}{2 \cdot q_l}\right)^2 \cdot \left(|S| + q_l\right) \cdot e^{-\frac{|S|}{q_l}}; \end{aligned} \tag{18}$$

$$C_G(S) = \frac{(1-\alpha)^2}{\sqrt{2\pi} \cdot \left(\sigma_{lG}^2 + \sigma_{lG}^2\right)^{\frac{1}{2}}} \cdot e^{-\frac{S^2}{2\cdot\left(\sigma_{lG}^2+\sigma_{lG}^2\right)}}; \tag{19}$$

$$C_{DE}(S) = \frac{e^{-\frac{|S|}{\lambda_{l\,DE}}}}{4 \cdot \lambda_{l\,DE}} \cdot 1 + \frac{|S|}{\lambda_{l\,DE}}\ . \tag{20}$$

Selection of the radar error probability density type by the criterion of the maximum horizontal overlap probability

The previously introduced rule for selecting the analytical type of the probability density for errors in measuring the aircraft coordinates using the reference radar allows consideration of $C(S_j)$ values in two scenarios of using the reference radar:

a) use of four competing reference radars for the same linear RMS_l:

$$RMS_l = \sigma_{l\,G\_G} = \sigma_{l\,DE\_DE} = \sigma_{l\,G} = \sigma_{l\,DE};$$

b) use of four competing reference radars for the same range to the aircraft:

$$R = R_{G\_G} = R_{DE\_DE} = R_G = R_{DE}$$

The results of testing the four types of reference radar densities for scenario a) are presented in Table 1. For scenario a), the $C(S_j)$ density test results for $10 \le S_j \le 20\,[km]$ are not presented, since the $C_{DE\_DE}(S_j)$ density is unconditionally greater than all other densities.

The results of testing the four types of densities for scenario b) are presented in Tables 2 and 3.

Comparison of the $C(S_j)$ values in Tables 1, 2 and 3 shows that none of the density types (17), (18), (19) and (20) is maximum for all values R, σ_l and S_j. Since there are (3×28) values in each table, let us introduce the aggregated measure of the aircraft overlap probability density as a sum of $C(S_j)$ values for each row of Table 1, 2 or 3.

Table 1. $C(S)$ values for various models of the reference radar azimuth errors depending on linear errors in determining the aircraft coordinates and observed intervals between aircraft that are less than the established minimum ($0 < S < S_{\min}$).

Linear error RMSs [km]	$C(S)$ density type	S [km]						
		1	2	3	4	5	7	9
0.150	$C_{G\_G}(S)$	0.0117	6.771×10^{-5}	2.135×10^{-7}	2.240×10^{-10}	3.376×10^{-14}	2.173×10^{-24}	5.602×10^{-38}
	$C_{DE\_DE}(S)$	0.0028	7.264×10^{-5}	3.850×10^{-6}	2.045×10^{-7}	1.086×10^{-8}	3.064×10^{-11}	8.641×10^{-14}
	$C_G(S)$	2.811×10^{-5}	9.383×10^{-20}	6.996×10^{-44}	1.165×10^{-77}	4.335×10^{-121}	6.685×10^{-237}	0
	$C_{DE}(S)$	0.0020	3.028×10^{-7}	3.592×10^{-11}	3.819×10^{-15}	3.820×10^{-19}	3.439×10^{-27}	2.851×10^{-35}

0.300	$C_{G\_G}(S)$	0.0263	0.0059	6.116×10^{-4}	3.386×10^{-5}	1.836×10^{-6}	4.384×10^{-9}	1.756×10^{-12}
	$C_{DE\_DE}(S)$	0.0563	0.0014	1.651×10^{-4}	3.632×10^{-5}	8.354×10^{-6}	4.437×10^{-7}	2.357×10^{-8}
	$C_G(S)$	0.0585	1.405×10^{-5}	1.306×10^{-11}	4.691×10^{-20}	6.515×10^{-31}	7.261×10^{-60}	1.807×10^{-98}
	$C_{DE}(S)$	0.0604	9.885×10^{-4}	1.287×10^{-5}	1.514×10^{-7}	1.680×10^{-9}	1.870×10^{-13}	1.421×10^{-17}
0.500	$C_{G\_G}(S)$	0.1037	0.0116	0.0050	0.0016	3.670×10^{-4}	1.113×10^{-4}	3.603×10^{-7}
	$C_{DE\_DE}(S)$	0.1549	0.0153	0.0016	3.001×10^{-4}	9.907×10^{-5}	1.623×10^{-4}	2.787×10^{-6}
	$C_G(S)$	0.2076	0.0103	6.928×10^{-9}	6.349×10^{-8}	7.835×10^{-12}	2.958×10^{-22}	3.746×10^{-36}
	$C_{DE}(S)$	0.1600	0.0164	0.0014	1.063×10^{-4}	7.723×10^{-6}	3.706×10^{-8}	1.647×10^{-16}

Table 2: $C(S)$ values for various models of the reference radar azimuth errors depending on the range to the aircraft and observed intervals between aircraft that are less than the established minimum($0 < S < S_{\min}$).

Range to the aircraft (RANGE) [km]	$C(S)$ density type	S [km]						
		1	2	3	4	5	7	9
60×1.852	$C_{G\_G}(S)$	0.0128	9.897×10^{-5}	3.778×10^{-7}	6.221×10^{-10}	1.699×10^{-13}	5.333×10^{-23}	1.138×10^{-35}
	$C_{DE\_DE}(S)$	5.478×10^{-4}	7.065×10^{-6}	9.691×10^{-8}	1.329×10^{-9}	1.823×10^{-11}	3.429×10^{-15}	6.447×10^{-19}
	$C_G(S)$	5.748×10^{-5}	1.823×10^{-18}	5.789×10^{-41}	1.842×10^{-72}	5.873×10^{-113}	6.001×10^{-221}	0
	$C_{DE}(S)$	0.0026	5.406×10^{-7}	8.861×10^{-11}	1.302×10^{-14}	1.800×10^{-18}	3.098×10^{-26}	4.908×10^{-34}
130×1.852	$C_{G\_G}(S)$	0.0318	0.0076	0.0012	1.110×10^{-4}	7.725×10^{-6}	4.613×10^{-8}	9.149×10^{-11}
	$C_{DE\_DE}(S)$	0.0192	3.728×10^{-4}	4.575×10^{-5}	6.308×10^{-6}	8.713×10^{-7}	1.662×10^{-8}	3.171×10^{-10}
	$C_G(S)$	0.0922	1.228×10^{-4}	1.981×10^{-9}	3.867×10^{-16}	9.139×10^{-25}	9.057×10^{-48}	1.928×10^{-78}
	$C_{DE}(S)$	0.0818	0.0022	4.792×10^{-5}	9.387×10^{-7}	1.736×10^{-8}	5.375×10^{-12}	1.537×10^{-15}
200×1.852	$C_{G\_G}(S)$	0.1123	0.0118	0.0053	0.0018	4.639×10^{-4}	1.658×10^{-5}	5.845×10^{-7}
	$C_{DE\_DE}(S)$	0.0799	0.0028	2.746×10^{-4}	6.619×10^{-5}	1.811×10^{-5}	1.380×10^{-6}	1.053×10^{-7}
	$C_G(S)$	0.2144	0.0131	1.235×10^{-4}	1.806×10^{-7}	4.094×10^{-11}	7.816×10^{-21}	8.592×10^{-34}
	$C_{DE}(S)$	0.1660	0.0187	0.0017	1.466×10^{-4}	1.174×10^{-5}	6.835×10^{-8}	3.687×10^{-10}

Table 3: $C(S)$ values for various models of the reference radar azimuth errors depending on the range to the aircraft and observed intervals between aircraft that are close to the established minimum($S_{\min} \leq S \leq 2 \cdot S_{\min}$).

Range to the aircraft (RANGE) [km]	$C(S)$ density type	S [km]						
		10	11	12	14	16	18	20
60×1.852	$C_{G\_G}(S)$	3.410×10^{-43}	1.650×10^{-51}	1.289×10^{-60}	3.312×10^{-81}	5.782×10^{-105}	6.861×10^{-132}	5.534×10^{-162}
	$C_{DE\_DE}(S)$	8.840×10^{-21}	1.212×10^{-22}	1.662×10^{-24}	3.123×10^{-28}	5.868×10^{-32}	1.102×10^{-35}	2.071×10^{-39}
	$C_G(S)$	0	0	0	0	0	0	0
	$C_{DE}(S)$	6.057×10^{-38}	7.402×10^{-42}	8.972×10^{-46}	1.293×10^{-53}	1.825×10^{-61}	2.537×10^{-69}	3.484×10^{-77}
130×1.852	$C_{G\_G}(S)$	2.284×10^{-12}	3.868×10^{-14}	4.441×10^{-16}	1.825×10^{-20}	1.587×10^{-25}	2.916×10^{-31}	1.134×10^{-37}
	$C_{DE\_DE}(S)$	4.380×10^{-11}	6.049×10^{-12}	8.355×10^{-13}	1.594×10^{-14}	3.040×10^{-16}	5.798×10^{-18}	1.106×10^{-19}
	$C_G(S)$	1.185×10^{-96}	8.815×10^{-117}	7.939×10^{-139}	1.143×10^{-188}	3.533×10^{-246}	2.346×10^{-311}	0
	$C_{DE}(S)$	2.549×10^{-17}	4.187×10^{-19}	6.825×10^{-21}	1.779×10^{-24}	4.544×10^{-28}	1.143×10^{-31}	2.842×10^{-35}
200×1.852	$C_{G\_G}(S)$	1.133×10^{-7}	1.980×10^{-8}	2.986×10^{-9}	4.184×10^{-11}	3.044×10^{-13}	1.148×10^{-15}	2.247×10^{-18}
	$C_{DE\_DE}(S)$	2.907×10^{-8}	8.029×10^{-9}	2.217×10^{-9}	1.691×10^{-10}	1.290×10^{-11}	9.835×10^{-13}	7.501×10^{-14}
	$C_G(S)$	1.737×10^{-41}	5.439×10^{-50}	2.638×10^{-59}	2.307×10^{-80}	1.162×10^{-104}	3.5264×10^{-132}	5.627×10^{-163}
	$C_{DE}(S)$	2.658×10^{-11}	1.899×10^{-12}	1.346×10^{-13}	6.632×10^{-16}	3.206×10^{-18}	1.526×10^{-20}	7.182×10^{-23}

RESULTS AND DISCUSSION

In Table 1, for $\sigma_l = 0.150\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{G\_G}(S)$ densities.

For $\sigma_l = 0.300\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{DE}(S)$ densities.

For $\sigma_l = 0.500\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_G(S)$ densities.

In Table 2, for $R = 60 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{G\_G}(S)$ densities.

For $R = 130 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_G(S)$ densities.

For $R = 200 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_G(S)$ densities.

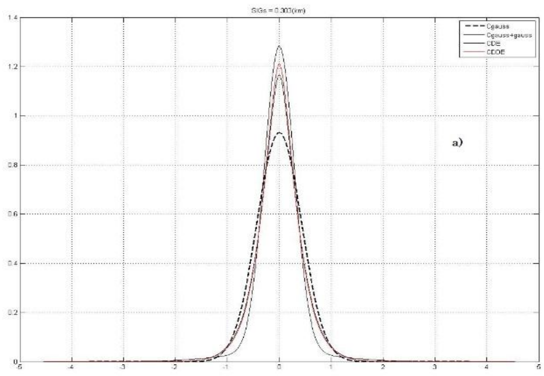
Note that in Table 2, $\sum_j C_{DE\_DE}(S_j)$ is not maximum for any R, in spite of the fact that the azimuthal RMS of model (2) is significantly smaller than the azimuth RMSsof models (1), (11) and (12) (0.0529 [deg] versus 0.0801 [deg]).

In Table 3, for $R = 60 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{DE\_DE}(S)$ densities.

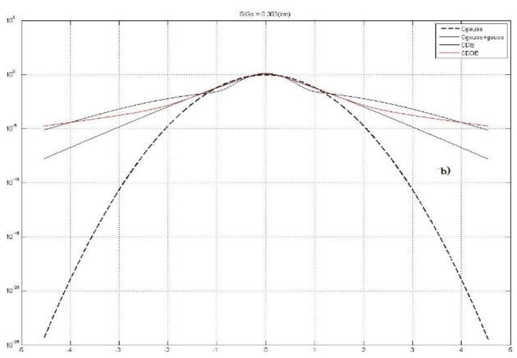
For $R = 130 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{DE\_DE}(S)$ densities.

For $R = 200 \times 1.852\,[km]$ the maximum value of $\sum_j C(S_j)$ is achieved at $C_{G\_G}(S)$ densities.

Figure 1 illustrates to some extent the results of the analysis of the contents for Tables 1, 2 and 3.



(a)



(b)

Figure 1: Comparison of the aircraft overlap probability densities $C_{G\_G}(S)$, $C_{DE\_DE}(S)$, $C_G(S)$ and $C_{DE}(S)$ for the same RMS values of the linear errors in determining the aircraft coordinates for various models of the reference radar azimuth errors: a) – linear scale; b) –semilogarithmic scale.

CONCLUSION

The calculations of the values of aircraft overlap probability densities for various models of errors in determining the aircraft coordinates using the reference radar show that none of the $C(S_j)$ densities can be regarded as the density at which the maximum pessimistic result (maximum in magnitude) is obtained for intervals S_j close to the minimum ($S_{\min} \le S_j \le 2 \cdot S_{\min}$), and for intervals less than the minimum ($0 < S_j < S_{\min}$).

It follows that for the assessment of theaircraft collision risk during flights along the area navigation routes with RNAV 1, RNAV 2 and/or RNAV 5 specifications, for each $0 < S_j \le 2 \cdot S_{\min}$ value, the $HOP(S_j)$ value must be calculated for all four types of the reference radar error densities, but for safety assessment, for example as in [9, 15, 19], the maximum $HOP(S_j)$ value must be used.

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