



National Aviation University of Ukraine
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Risk assessment of mid-air collision based on positioning performance by navigational aids

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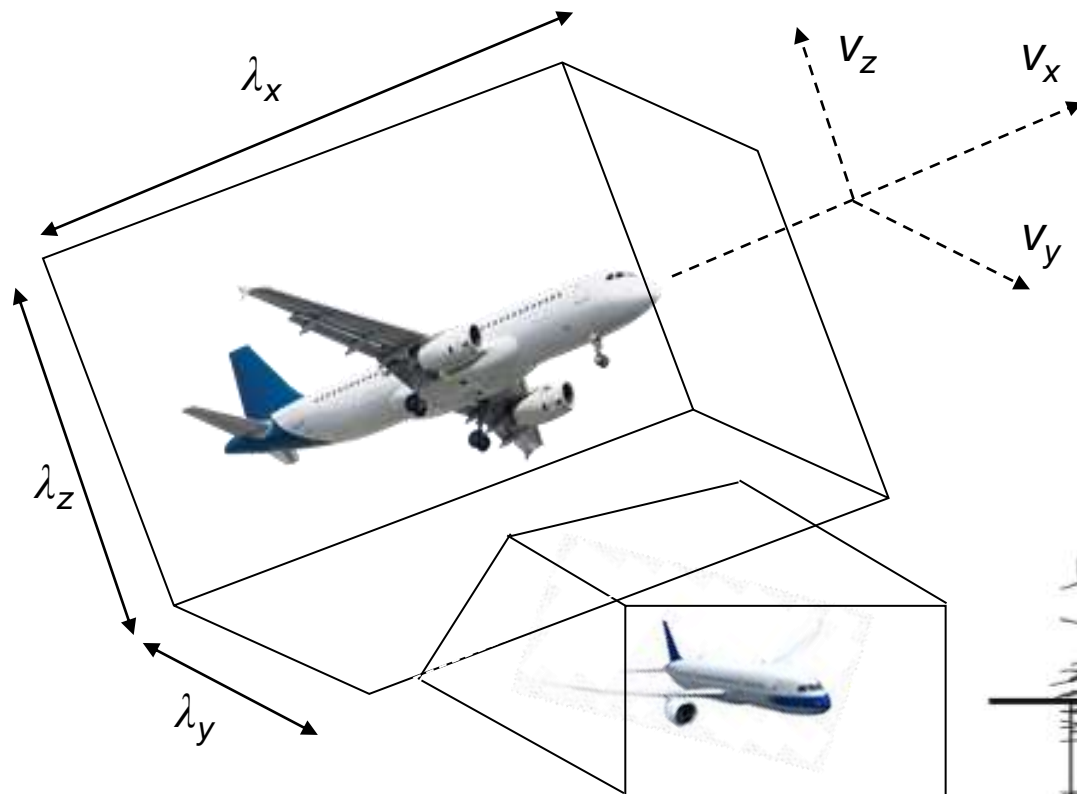


Mid-air collision

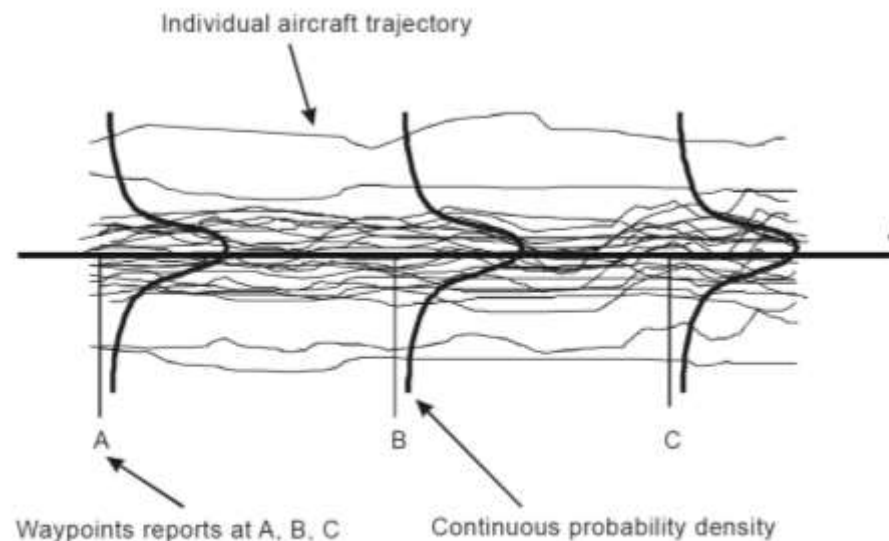
- Mid-Air collision is referenced to one of the main safety category
- involving both airplanes and mostly resulting in catastrophe
- wide usage of digital automatic systems reduce risk
- in a period of 2014-2018 years, only one accident happened
- risk of mid-air collision is estimated based on probabilities of airplane deviations from predefined trajectories, due to the rare frequency of accident occurrence and extremely low size of statistic.



model for risk assessment



We would like to provide an overall study of the influence of **errors of positioning system** into the probability of **mid-air collision** in the horizontal plane for civil aviation.





Aircraft on-board equipment for positioning

Global Navigation Satellite System
(GPS, GLONASS, GALILEO, BeiDou)

Inertial Navigation System
(IRS, AHRS)

Position by pair of navigational aids
DME, VOR (DME/DME, VOR/DME, VOR/VOR)
in Flight Management System

Errors of Global Navigation Satellite Systems

- large spatial variation in ionospheric delay
- **Interference from ground based radio equipment**
- **jamming of radio waves**
- Refraction from obstacles (multipath error)
- Geometric factor of the satellite segment



Accuracy of on-board positioning system

Total System Error (TSE)

$$\text{TSE}^2 = \text{NSE}^2 + \text{FTE}^2 + \text{PDE}^2$$

NSE

Navigation system error



FTE

Flight technical error



*depends on piloting mode: manual – 0.5 NM,
flight director – 0.25NM, autopilot – 0.125 NM*

PDE - Path definition error (PDE=0)



Accuracy of position by pair of navigational aids

DME/DME

$$NSE_{DME/DME}^2 = 4 \frac{\sigma_{DME1}^2 + \sigma_{DME2}^2}{\sin(\alpha)^2},$$

where σ_{DME1} , σ_{DME2} are errors of the distance measurement to DME 1 and DME 2;
 α is an angle between the directions to DMEs in pair.

VOR/VOR

$$NSE_{VOR/VOR}^2 = 4 \frac{\sigma_{VOR}^2 (d_{VOR1}^2 + d_{VOR2}^2)}{\sin(\alpha)^2},$$

where σ_{VOR} is an error of angle measurement in VOR system in radians;
 $d_{VOR1,2}$ are distances to VORs; α is the angle between the directions to VORs.

VOR/DME

$$NSE_{VOR/DME}^2 = 4(\sigma_{DME}^2 + d^2 \sigma_{VOR}^2),$$

where d is a horizontal range to a navigational aid.



Risk of mid-air collision

Risk of mid-air can be represented in the form of probability of unplanned airplane deviation from cleared trajectory to safety volume of other airspace user.

➤ probability density functions may be used for stochastic trajectory analysis

$$\rho(y) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(y-\mu)^2}{2\sigma^2}\right), \quad P\{a \leq y \leq b\} = \int_a^b \rho(y)dy,$$

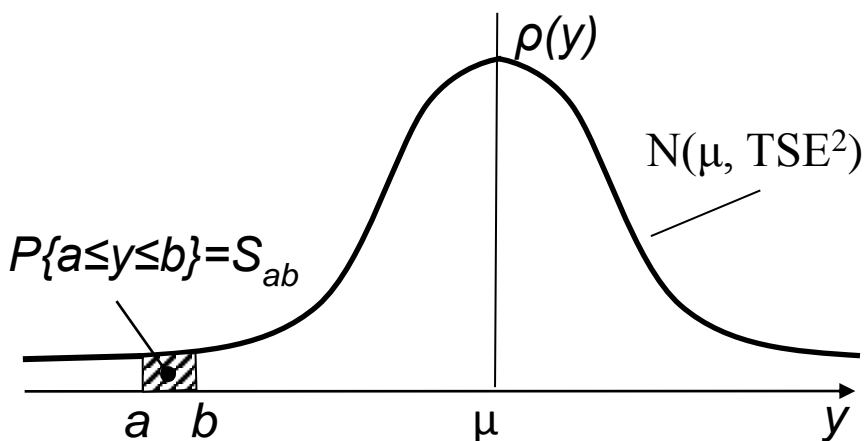
where σ is a mean squared deviation, μ is a mean value or airplane location.

➤ Risk of mid-air collision is

$$R_{AB} = P_A\{a \leq y \leq b\}P_B\{a \leq y \leq b\},$$

In the case of polyconflict:

$$R_p = \prod_{i=1}^n P_i\{a \leq y \leq b\},$$





Risk of mid-air collision

Bivariate normal distribution density function is used as an error model in order to take into account lateral and longitudinal airplane deviations:

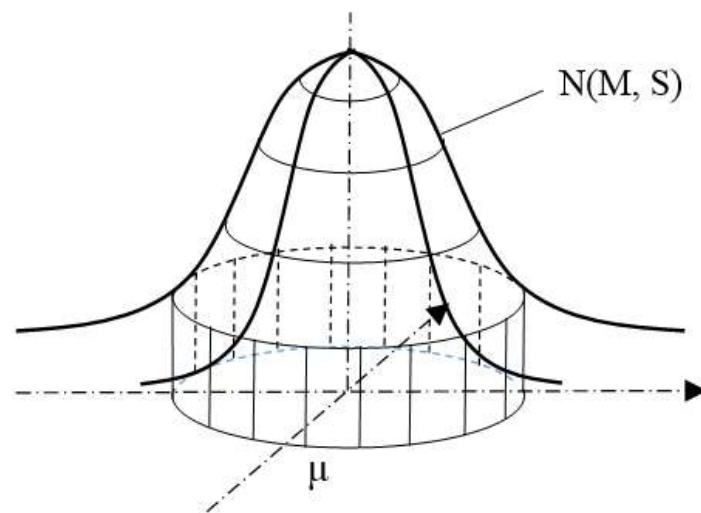
$$\rho(X) = \frac{1}{2\pi|S|^{-0.5}} \exp\left(-\frac{(X-M)^T(X-M)}{2S}\right),$$

where $X=[x,y]$ are measurements of airplane location; $M=[\mu_1, \mu_2]$ are coordinates of the aircraft location in some reference frame; S is a diagonal matrix of TSE:

$$S = \text{diag}([TSE^2, TSE^2]).$$

Probability of airplane getting in a rectangle with a size λ_x and λ_y may be estimated as follows for bivariate PDF:

$$P\{x \in \lambda_x, y \in \lambda_y\} = \iint_{\lambda_x, \lambda_y} \rho([x, y]) dx dy$$



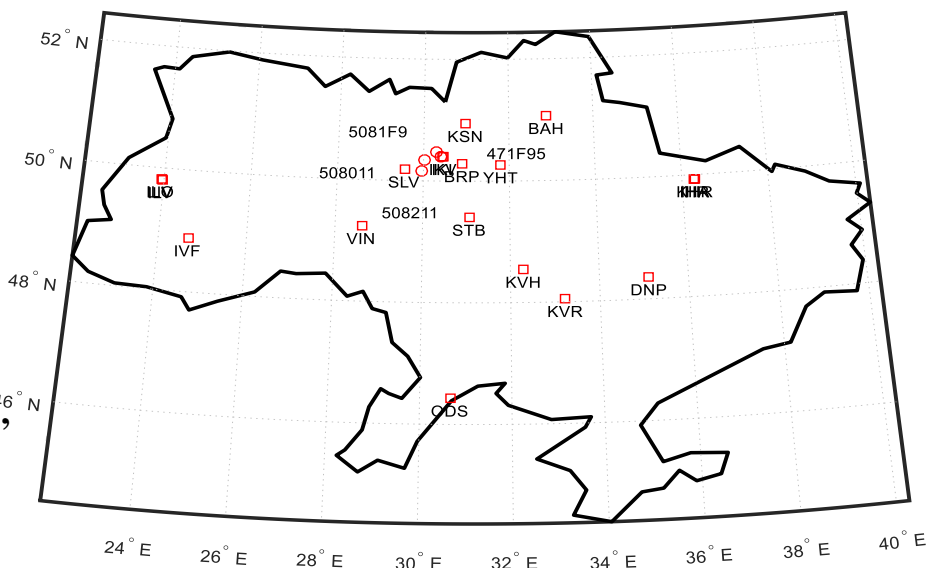


NUMERICAL DEMONSTRATION

- use live air traffic data “1090ES”
- Position reports are received by Software-Defined Radios (SDR) based on RTL2832U chipset.
- Experimental recordings took place in coordinates with latitude: 50.43899 N and longitude: 30.43012 E
- at 15.47 UTC time on August 14, 2020.
- Data contains non-synchronize air traffic coordinates, measured for a different time scales. Spline functions are used for data interpolation to unique time.



A network of navigational aids within Ukrainian airspace consists of 12 DMEs (BAH, IHA, IHR, IKI, IKV, KSN, KVR, ILO, ILV, STB, VIN, YHT) and 8 collocated VOR and DMEs (BRP, DNP, IVF, KHR, KVH, LIV, ODS, SLV)





Input data

TABLE 1. Airspace users and effective pairs of Navigational aids

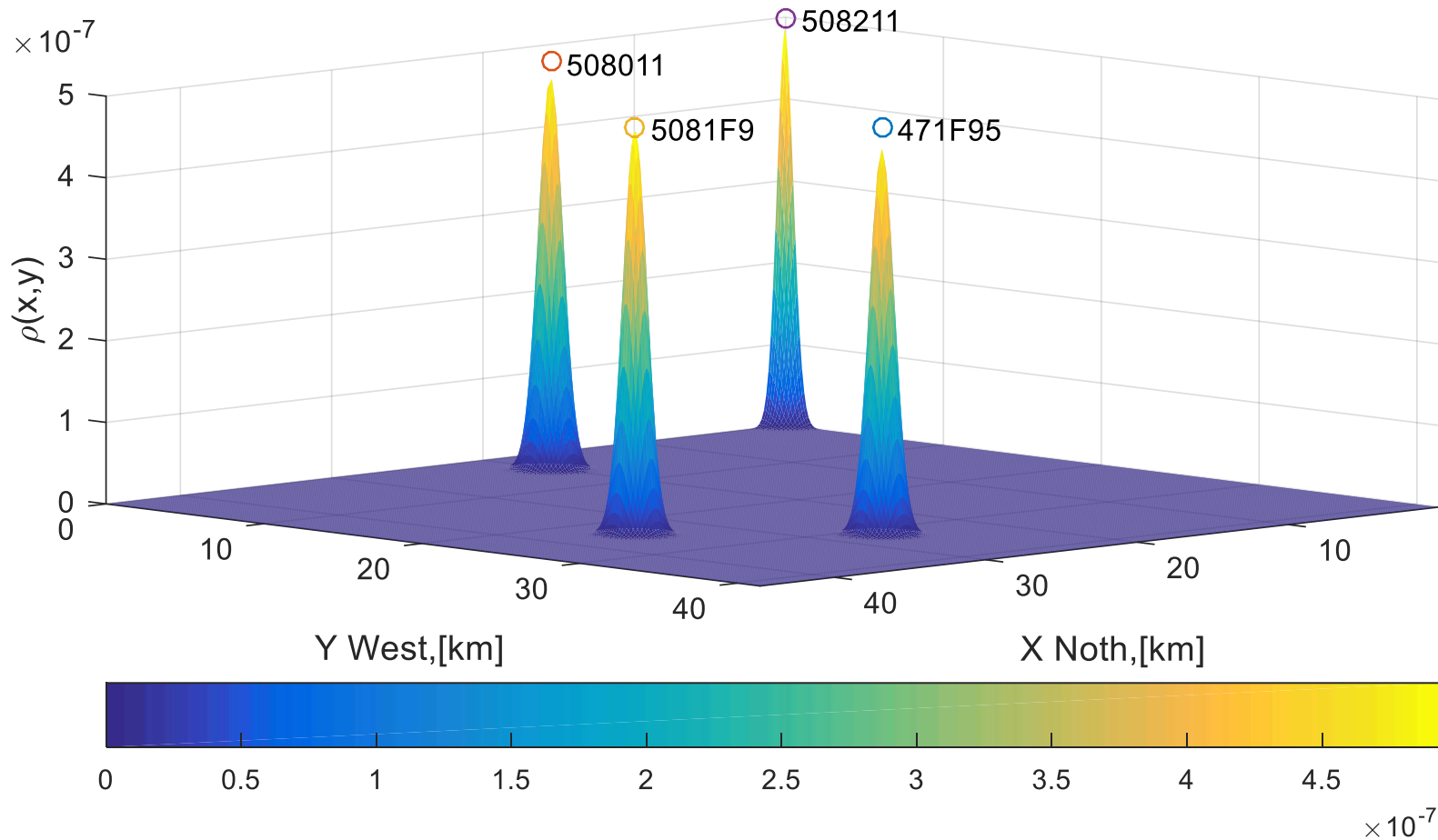
Airplane ICAO address	Latitude, deg	Longitude, deg	Altitude, ft	Effective pair		
				DME/DME	VOR/VOR	VOR/DME
471F95	50.4	30.404	875	'BRP' 'KSN'	'BRP' 'KSN'	'IKI'
508011	50.343	30.022	4084	'SLV' 'STB'	'BRP' 'SLV'	'IKI'
5081F9	50.476	30.298	2546	'IKI' 'KSN'	'IKI' 'SLV'	'IKI'
508211	50.162	29.96	13910	'KSN' 'STB'	'KSN' 'SLV'	'SLV'

TABLE 2. TSE for positioning by Navigational aids

Airplane ICAO address	TSE, NM		
	DME/DME	VOR/VOR	VOR/DME
471F95	0.3134	1.6001	0.2386
508011	0.3106	2.4803	0.6197
5081F9	0.3059	1.2479	0.3412
508211	0.3074	2.6347	0.5769

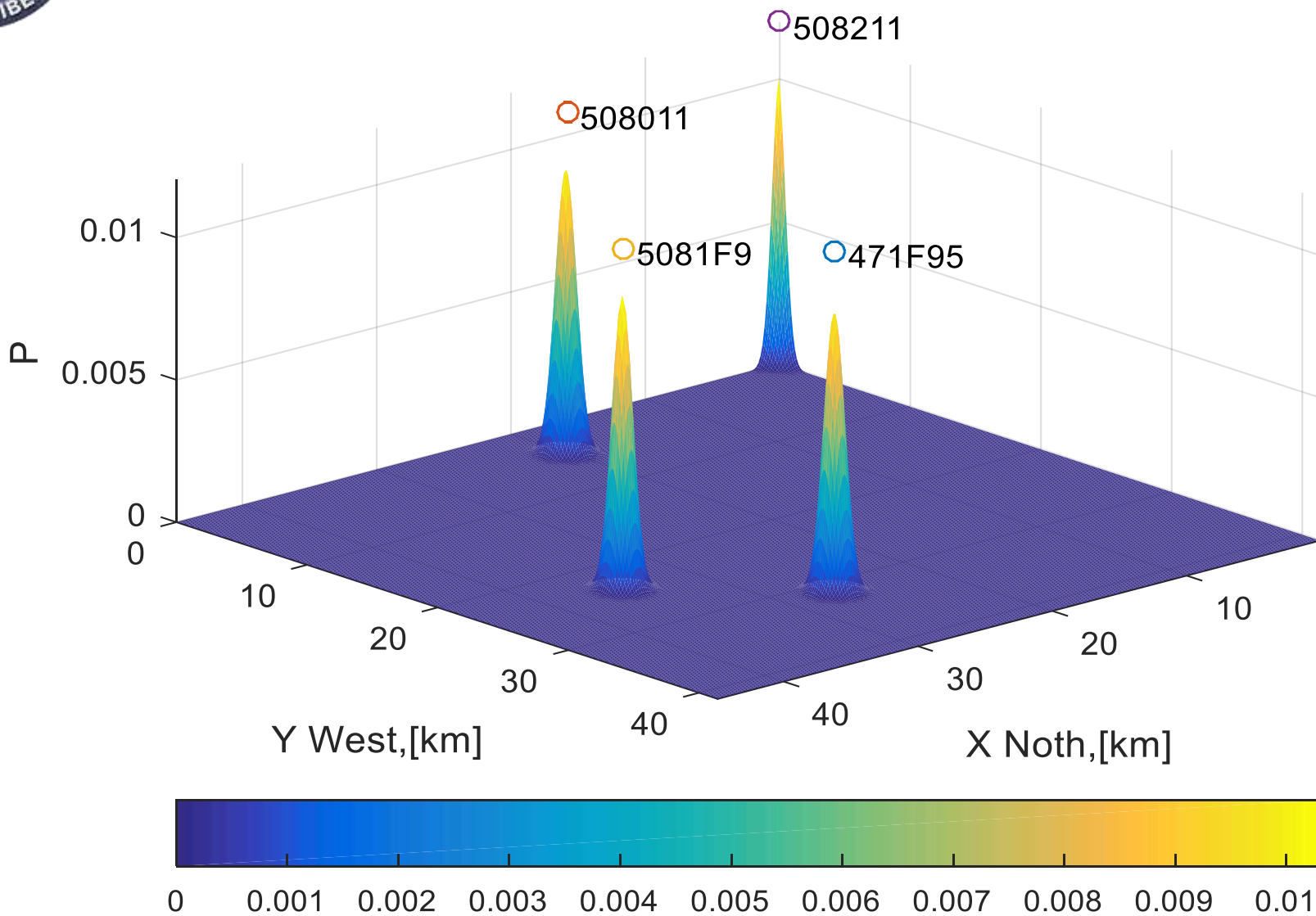


Probability Density Functions





Probability of airplane getting in the safety region cased by error of positioning





Risk of a mid-air collision

Conflict scenario		Risk of mid-air collision
471F95	508011	3.6×10^{-64}
471F95	5081F9	2.4×10^{-43}
508011	5081F9	2.5×10^{-206}
508011	508211	1.1×10^{-184}



CONCLUSION

Results of the represented study help to understand the impact of on-board positioning system errors on aviation safety in case of primary positioning system lock and operation by navigational aids. Obtained risk values for the safety category of mid-air collision for different conflict scenarios in live air traffic data summarize performance of positioning system and geometry of airspace user location in space.

Proposed approach may be useful in the task of total risk of mid-air collision as well as safety assessment. Also, obtained results can be accumulated for tasks of risk-based collision avoidance and safe air traffic planning.

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