Risk of Vertical Separation Loss at En-Route Phase of Airplane Flight

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Abstract

Safety of air transportation grounds on the exact following of preplanned trajectory by each airspace user. Different degradation factors actions on normal airplane operation lead to deviations out of cleared flight level that affect aviation safety level. In the paper we propose to use airplane trajectory data transferred by Automatic Dependent Surveillance-Broadcast equipment to estimate the risk of vertical separation loss. Risk is estimated as an area below the Probability Density Function of airplane deviation within altitude perils of cleared flight level. Data of barometrical altimeter measurements are used to fit double exponential and Triple Univariate Generalized Error Distribution probability density functions. A method of Maximum Posterior Probability is used to identify the flight phase with cleared flight level. Barometric altitude at the en-route phase of flight is only used. Proposed approach makes it possible to estimate risks by airplane type, airline, flight connection, pilot staff, flight route, or by part of airspace. As an example, a three months statistic of flight connection between Boryspil and Kharkiv airports is used to estimate the risk of vertical separation loss.

Keywords

Risk, aviation safety, air traffic, vertical separation, barometric altimeter, probability density function, TUGED

1. Introduction

Operation of global air transportation system grounds on insuring a particular level of flight safety. The safety of air transportation depends on action of different factors in normal airplane operation [1, 2]. Excessive action of some factors, or their combinations can lead to an incident or even airplane catastrophe. Therefore, the level of flight safety is under continuous control in order to identify the condition of beginning process of reducing level of flight safety.

The level of flight safety can be estimated by statistical analysis of dangerous events that took place during airplane operation to the number of flights, passengers, or a particular level of flight time. All reduced safety events in aviation are classified by incidents and accidents. An accident is an event with airplane in which any person has been seriously injured or fatalities or airplane structure has serious damage which corresponds to total airplane loss [3]. An incident is another than accident event, that took place during airplane operation and reduce flight safety level. Results

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of statistical analysis indicate that 221 accidents have occurred from 2017 to 2021 with 1035 fatalities in civil aviation [4]. Aviation safety categories are introduced to analyze degradation factors action into airplane flight. The most frequently used accident safety categories include runway-taxiway excursion, undershoot, controlled flight into terrain, in-flight damage, loss of control during en-route, and hard landing. Results of safety analysis for accident frequency and risk of fatality measured per flight is represented in Figure 1 [4]. Analysis of data indicates that runway-taxiway incursion is the most frequent event with 25% of all accidents, however, the risk of fatality is one of the lowest. On the other side risk of fatal cases is the highest for the category of control loss during en-route phase of flight with a small frequency of occurrence. It indicates that category loss of control during en-route is the most dangerous based on the number of fatalists.

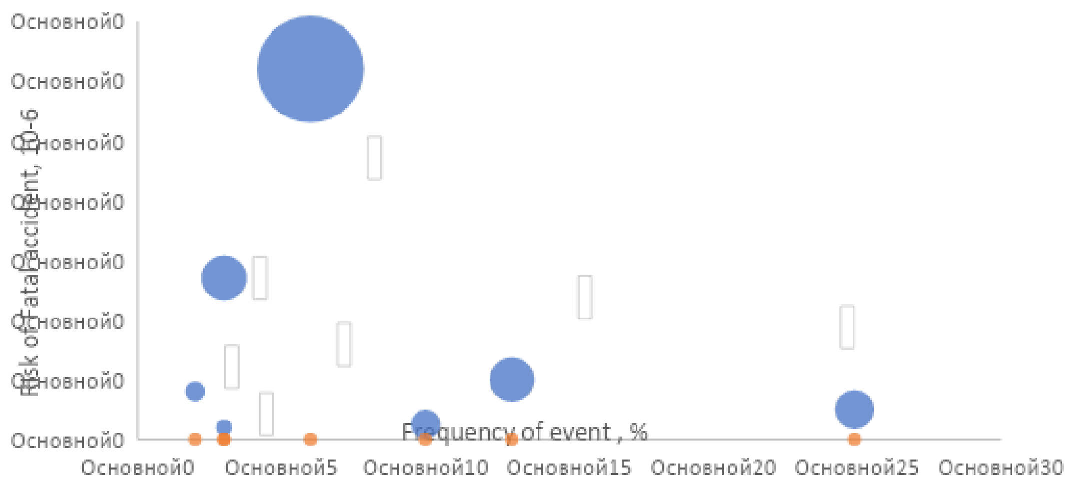

Figure 1: Statistic of accidents category for 2017-2021

Loss of control category includes a list of degradation factor influences during normal flight at en-route state. Most cases include different equipment failure occurrences and human factor action [5]. Advanced reliability analysis of equipment can minimize the action of this factor and improve flight safety [6, 7].

Another approach to air traffic safety estimation grounds on using Probability Density Functions (PDF) which describe airplane deviations from the predefined trajectory. In this case, PDF is recovered from big data analysis of airplane actual trajectories, which can be measured by different sensors. In this case, a precise radar [8, 9] or Global Navigation Satellite System (GNSS) can be used to obtain precise airplane trajectory measurements [10].

The risk of airplane deviations on parallel routes is studied with a help of a double exponential PDF [11]. Triple Univariate Generalized Error Distribution is used to take into account influence of rare events, flight technical, and navigation errors [12] on airplane deviations from the centerline of flight route in horizontal plane [13]. Also, normal and double Laplacian PDF are used to estimate the risk of airplane deviation from cleared flight level in vertical plane [14]. The level of airplane deviations from cleared flight level is an important parameter that affects flight safety, due to using a flight leveling system in vertical plane to control air traffic flow.

In this paper, we study particular airplane deviations from cleared flight level in order to estimate probability of vertical separation loss, which took place during en-route phase of the flight. Estimated risk values help to identify the current level of flight safety.

2. Flight leveling system

An air traffic system uses a vertical division of flight routes into flight levels (FL). Vertical separation between airplanes is done by flight level height. Flight levels are coded by numbers of 100 ft and start from 100 FL up to the whole used altitudes for air traffic. Below 8850 m (290 FL) height of each level is 300 m. Also, equipment and visual flight rules are used below 290 FL where the most weather fenomenas negative action are concentrated [15, 16]. Above 290 FL vertical separation in 600 m is used for flights by equipment [17]. Many airspaces include areas of Reduced Vertical Separation Minimum (RVSM) inside which the height of flight levels is 300 m in the range of 290 FL – 410 FL [18]. RVSM is designed to increase the capacity of airspace.

Air traffic uses a barometrical altitude to count flight levels. Barometric altimeter uses a formula of static pressure dependence on altitude. Static pressure is reduced with increasing altitude due to changing the number of gases in space. A set of hypsometric formulas are used for different atmospheric layers to measure altitude.

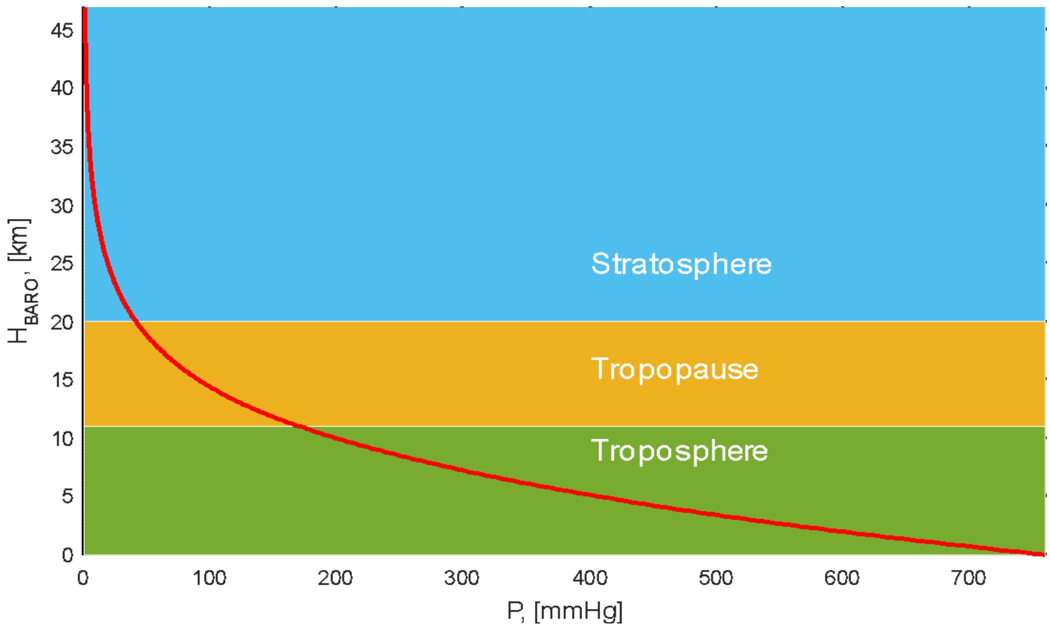

Figure 2: Static pressure dependents on altitude

Within the troposphere atmospheric layer (below 11000 m) altitude can be calculated by following hypsometric formula:

$$H(p) = \frac{T_{tropo}}{\tau_{tropo}}\left[1 - \left(\frac{p}{p_{tropo}}\right)^{\frac{\tau_{tropo}R}{g}}\right], \tag{1}$$

where p_{tropo}=760 [mmHg] is standard pressure level, T_{tropo}=288.15 [K] is the standard temperature, g=9.8 [m/s^2] is a gravity acceleration, R=8.314 [j/(mol·K)] is gas constant, τ_{tropo} is the temperature gradient, μ=0.0289644 [kg/mol] is air molar mass.

Inside of tropopause layer, another formula is used:

$$H(p) = h_{pause} - \left(\frac{RT_{pause}}{\mu g}\right) ln\left(\frac{p}{p_{pause}}\right), \quad (2)$$

where h_{pause}=11000 [m] is the bottom line of the layer, T_{pause}=216.66 [K] and p_{pause}=169.75 [mmHg] are temperature and pressure at starting line of tropopause .

Lower part of stratosphere (20 000 – 32 000 m):

$$h(p) = h_{strato} + \frac{T_{strato}}{\tau_{strato}}\left[\left(\frac{p}{p_{strato}}\right)^{\frac{-\tau_{strato}R}{\mu g}} - 1\right], \quad (3)$$

where h_{strato}=20000 [m] is the bottom line of the layer, T_{strato}=216.66 [K] and p_{strato}=41.065 [mmHg] are temperature and pressure at starting line of the stratosphere τ_{strato} is temperature gradient.

Hypsometric formulas give altitude by measured static pressure value. Also, barometric altitude is counted from the isobaric line of constant pressure which is called Mean Sea Level. A level of 760 mmHg is used as a standard pressure for isobaric line [19]. Each airspace user measures its barometric altitude from one unified isobaric level, which makes it possible to realize vertical separation with a help of flight levels. Measurements of static pressure at high speed moved airplane body introduce different types of errors which depends on airflow parameters and configuration of static pressure probes location. An error of static pressure measurements forms an error of altitude measurements [20].

3. Risk of vertical separation loss

Risk of vertical separation loss is a probability of airplane deviation out of cleared flight level perils. It may occuared in case of ecssevive errors of measurements action or uncorect operation of flight control system [21, 22]. This probability can be counted as the frequency of events happening. However, these deviations are referred to as very rare events, that require operating with a very long set of trajectory data, which may not be available. Therefore, such kind of probability can be estimated as an area under PDF out of a particular altitude frame. In this case, an assumption of deviation distribution should be made based on a particular scenario. Thus, normal PDF (NPDF), double exponential PDF (DEPDF), and Triple Univariate Generalized Error Distribution (TUGED) PDF can be used. Parameters of PDF are tuned based on available trajectory data.

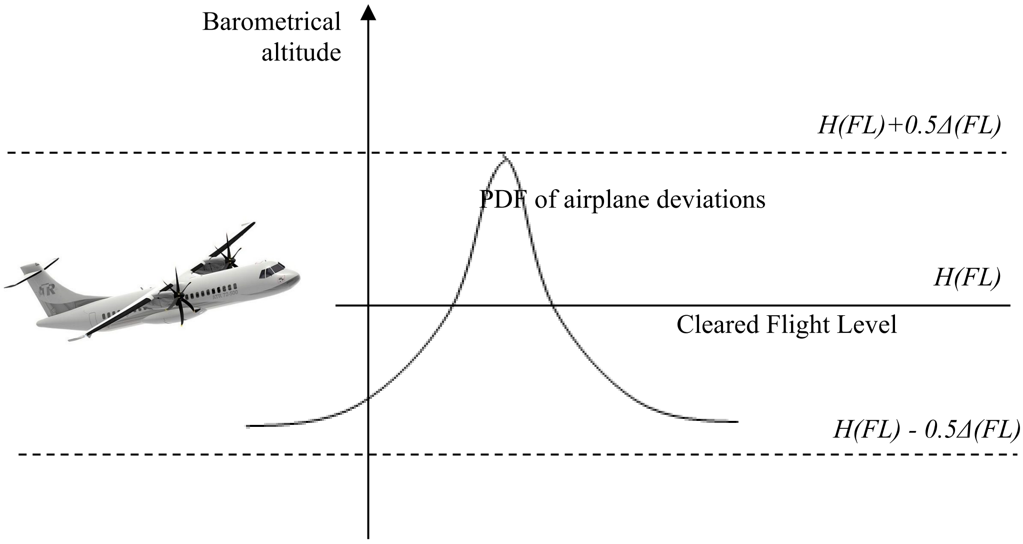

Figure 3: Probability of airplane deviations out of cleared flight level

Probability of airplane deviation can be estimated as follows:

$$R=P\{ H(FL) - 0.5\Delta(FL) < h(p) > H(FL)+0.5\Delta(FL)\}, \quad (4)$$

where *H(FL)* is a cleared flight level altitude, *Δ(FL)* is the height of cleared flight level, *h(p)* is a measured barometrical altitude.

Based on known PDF, risk R can be estimated as follows:

$$R = 1 - \int_{H(FL) - 0.5\Delta(FL)}^{H(FL)+0.5\Delta(FL)} \rho(h)dh, \quad (5)$$

where *ρ(h)* is particular PDF.

DEPDF is used in the scenario of normal barometrical error distribution and exponential distribution of appearance rare events. DEPDF includes a mix of two exponential functions one of them operates in the core, and another is mostly active in the tails sides. DEPDF can be represented in the following form [14]:

$$\rho_{DEPDF} = \frac{\alpha}{2a_1 b_1 \Gamma(b_1)} exp\left(-\left|\frac{h-\mu}{a_1}\right|^{b_1^{-1}}\right) + \frac{1-\alpha}{2a_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{h-\mu}{a_2}\right|^{b_2^{-1}}\right), \quad (6)$$

where a_1 and a_2 are scale factors; b_1 and b_2 are shape parameters; Γ is a gamma-Euler function; μ is mean value, α is a mix parameter.

TUGED model is used in the scenario taking into account three components of errors: error of barometrical altitude measurements, flight technical error [24], and appearance of rare events:

$$\rho(y) = \frac{\alpha}{2a_1 b_1 \Gamma(b_1)} exp\left(-\left|\frac{y-b_1}{a_1}\right|^{b_1^{-1}}\right) + \frac{\beta}{2a_2 b_2 \Gamma(b_2)} exp\left(-\left|\frac{y-b_2}{a_2}\right|^{b_2^{-1}}\right) + \frac{1-\alpha-\beta}{2a_3 b_3 \Gamma(b_3)} exp\left(-\left|\frac{y-b_3}{a_3}\right|^{b_3^{-1}}\right), \quad (7)$$

where a_3 is scale factor; b_3 is shape coefficient; α and β are weight coefficients of core.

The following constraints are applied in equation (7) [13]:

$$0 \le \alpha + \beta \le 1,$$
$$1 \le a \le \infty, \qquad (8)$$
$$0.5 \le b \le 1.$$

DEPDF is the more common model. TUGED in comparison with DEPDF helps to separate two different types of error action in the core of PDF.

4. Input data

As input, we use barometric altitude data transmitted by airplane transponder of Mode 1090ES under the Automatic Dependent Surveillance-Broadcast (ADS-B). According to ADS-B any airspace user should be equipped with a Mode 1090ES transponder and share in open format position report for anyone who needs it. Transmitted automatically digital message includes unique ICAO identification code of airplane and airborne position. Airborne position report consists of coded values of latitude, longitude, and barometrical altitude [23]. A Global Navigation Satellite System (GNSS) is used as a primary positioning sensor. In the case of GNSS lock, methods of positioning by pairs of navigational aids are used as a main backup technology [25, 26]. Also, an inertial navigation system can be initiated during a short period of time due to additive errors influence of gyroscopic sensors on board of heave airplanes [27, 28]. Decoded values of position reports can be used to track any airspace user including altitude measured on board by Air Data System or by a simple barometrical altimeter. Due to the limited range of radio communication line, a network of software defined radios is used to collect the data along the whole airplane trajectory.

Raw barometric data set includes all altitudes from take-off to landing. Thus, another important task is the clusterization of altitude data into flight phases and use altitudes of en-route phase for evaluating parameters of PDF. A detector of flight phase is required due to the absence of these data and operation only with a barometrical data set. As an example, the altitude of flight SIA 391 for connection LTFM – WSSS is represented in Figure 4. Cleared flight level can be changed many times during one flight. For flight SIA 391 cleared flight level has been changed three times 360 FL, 380 FL, and 400 FL.

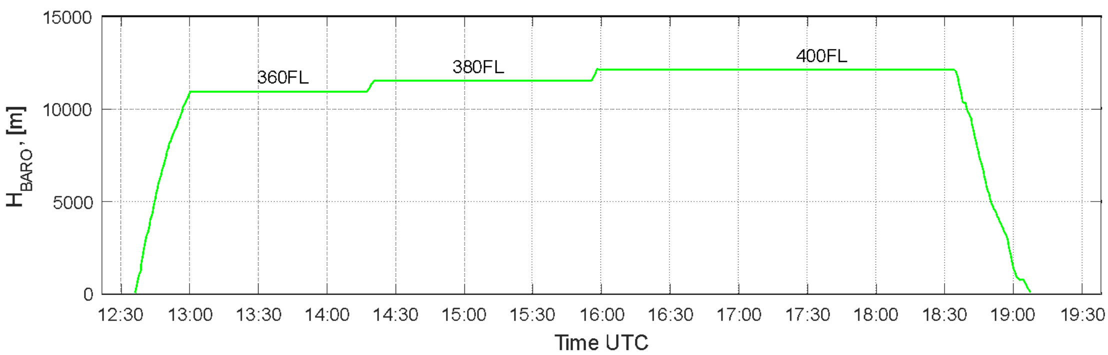

Figure 4: Airplane altitude for SIA 391 flight on October 26, 2022

En-route phase detection can be done by a simple trigger function based on vertical rate estimated by nearest altitude data and known time shifts between them [29]. However, this trigger does not take into account errors in altitude measurements [30]. The method of Maximum Posterior Probability (MPP) [31] gives better cauterization performance with minimal classification errors.

MPP method considers two hypotheses: the airplane is at en-route phase of flight – Q_{en} and airplane is at other phases – Q_0. Let's consider the actual state without any prior probability. Thus, the sum of prior probabilities of these hypotheses appearance form a full group:

$$P(Q_{en})+P(Q_0)=1 .$$

Also, we consider each of these hypotheses is equally probable:

$$P(Q_{en})=P(Q_0)=0.5.$$

MPP method grounds on estimation posterior probabilities of each hypothesis presents at each data point $P(Q/b_j)$ with a help of Bayes formula [31]:

$$P(Q_{en}/b_j) = \frac{P(Q_{en})P(b_j/Q_{en})}{P(Q_0)P(b_j/Q_0)+P(Q_{en})P(b_j/Q_{en})}, \tag{9}$$

$$P(Q_0/b_j) = \frac{P(Q_0)P(b_j/Q_0)}{P(Q_0)P(b_j/Q_0)+P(Q_{en})P(b_j/Q_{en})}, \tag{10}$$

where $P(bj/Q)$ is probability bj in the case of hypothesis Q evidence.

Detection of current phase is made by a maximum of posterior probability:

$$q = max\{P(Q_{en}/b_j), P(Q_0/b_j)\}, j = [1,2]. \tag{11}$$

The main advantages of MPP include:

- obtaining probability of correct decision q together with decision;
- indicates good performance in a noisy environment.

Bayes formula can be represented in form of PDFs using $\rho(b/Q)$ instead of $P(b/Q)$.

In this case, at the scale of parameter, a particular set of conditional PDF is fixed. Due to measuring barometric altitude under the Gaussian noise action, as a conditional PDF $\rho(b/Q)$ we use NPDF:

$$\rho(x)_i = \frac{1}{\sigma_i\sqrt{2\pi}} exp\left(-\frac{x-\mu_i}{2\sigma_i^2}\right), \tag{12}$$

where μ_i and σ_i are mean and standard deviation values.

In our detector, a vertical rate is used as the main classification parameter. A value of vertical rate is calculated by previous and current barometrical altitude in meters divided by the time between their measurements.

Fixed conditional PDF for both hypotheses are presented in Figure 5 and corresponding posterior probabilities in Figure 6 for the parameter of vertical rate.

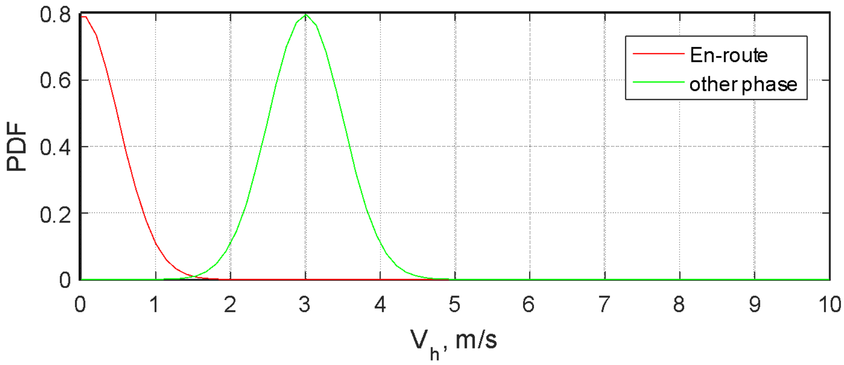

Figure 5: Conditional PDF for both hypotheses

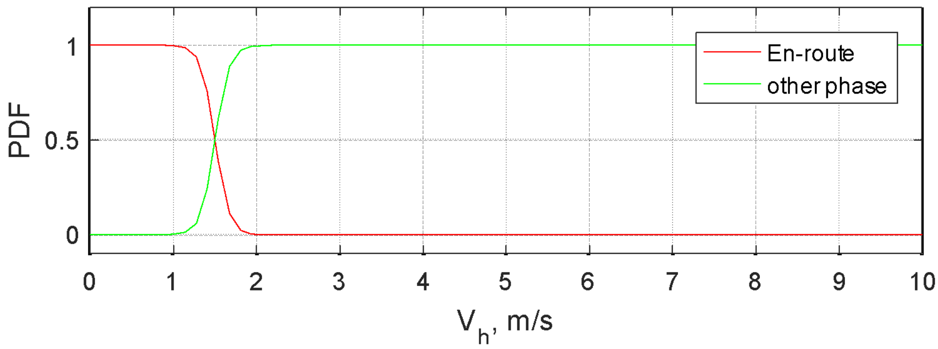

Figure 6: Posterior probabilities distributions

En-route flight phase detection with MPP makes it possible to grab only en-route altitude data to perform statistical data analysis of airplane deviations from cleared flight levels.

5. Numerical calculation

Verification of the proposed approach has been done by using real airplane trajectory data obtained by a network of software defined receivers including equipment located at the National Aviation University.

We use 83 unique realizations of local flight AUI 25 with a connection between Boryspil (UKBB) and Kharkiv (UKHH) international airports. These flights have been performed during three month period from October 01, 2019, to January 02, 2020. This flight was served 51 times by Boeing 737 and 32 times by ERJ-190 aircraft. Mean value of flight trajectory is 420 km. Mean value of flight time is 32 min. Flight paths of all flights are represented in Figure 7. It should be noted that we use data only in one direction from UKBB to UKHH. Trajectories variation in Figure 7 is a result of different schemes of Standard Instrument Departures (SID) and Arrival Route (STAR) used, during movement in a particular airport vicinity. A small range of flight connections does not require following exactly by the centerline of a preplanned flight plan. Therefore, in the most cases aircraft just try to keep direct flight from final point of SID to start point of STAR. Vertical profiles of these flights are presented in Figure 8. Also, due to the short range of flight connections, aircraft is at climbing and descending phases most of the time. En-route phase usually takes no more than 10 min for AUI 25. Also, a variety of flight levels are used: 250 FL, 270 FL, 290FL, 310FL, 330FL, and 350 FL. All flight levels are directed to support air traffic with a heading angle in the range from 0º to 180º.

The data processing is performed in the specialy developed software in Matlab enviroment.

Then we apply MMP for detection of en-route phase dataset, based on vertical speed calculated from barometrical altitudes. Obtained portions of altitude data we compare with altitude of cleared flight level centerline. Results of airplane deviations from the centerline are represented in the form histogram in Figure 9.

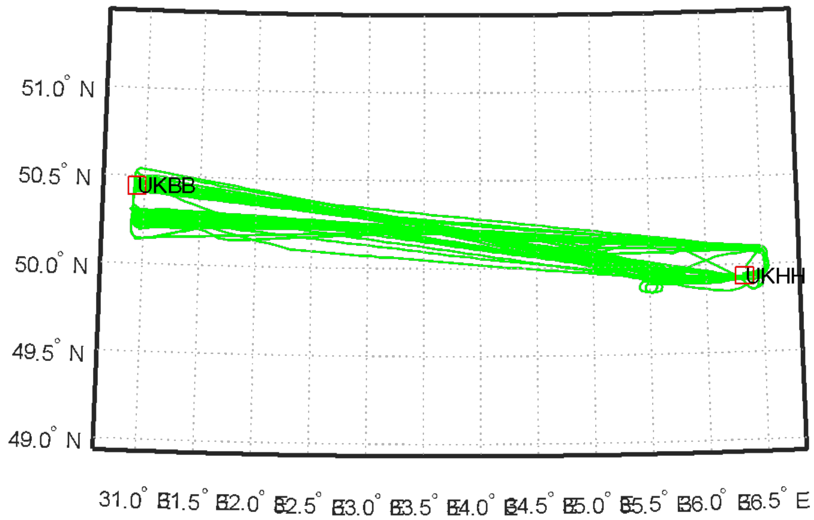

Figure 7: Trajectories variation for AUI 25 flight

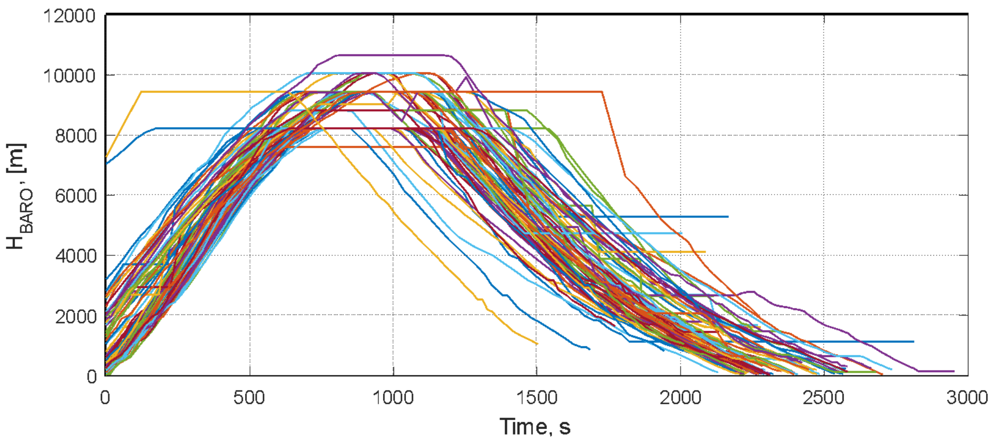

Figure 8: Vertical profile of AUI 25 flights

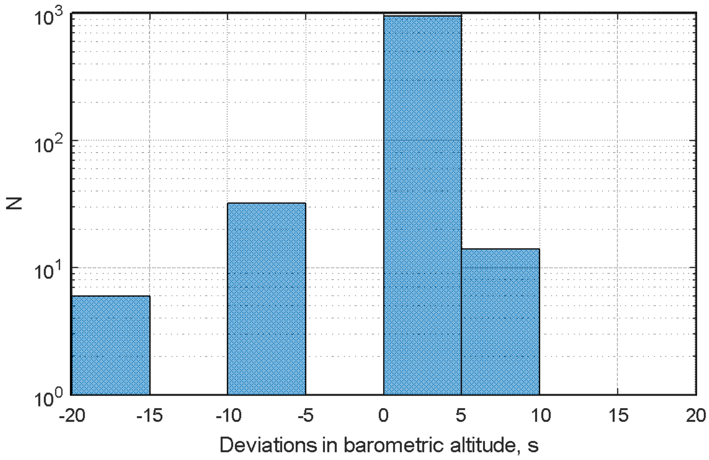

Figure 9: Histogram of airplane deviations from cleared flight level centerline

A Maximum Likelihood Method is used to estimate parameters of PDF based on deviations represented in Figure 9. Total size of input data is 997 data points. Mean value is -0.45m. Standard deviation is 5.45 m. Result of TUGED fitting to input data by Maximum Likelihood Method gives the following values for parameters:

$\alpha = 0.5$; $\beta = 0.4$; $\mu = 0$; $a_1 = 30$; $a_2 = 10$; $a_3 = 2$; $b_1 = 0.5$; $b_2 = 0.5$; $b_3 = 1$.

Results of PDFs fitting are presented in Figure 10.

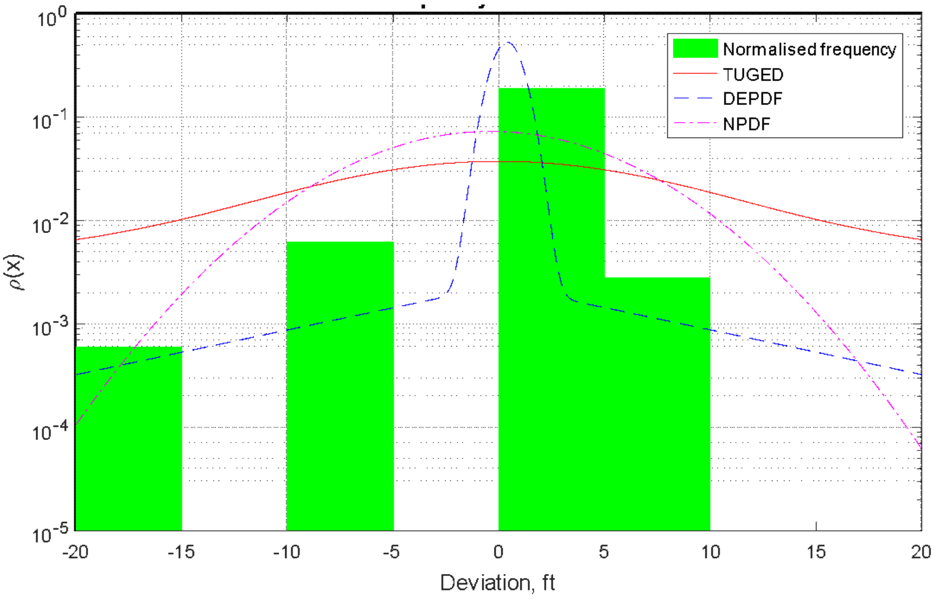

Figure 10: Results of PDF estimation

Risk of vertical separation loss is calculated by (5) taking into account that all flights are performed inside the area of Reduced vertical separation minimum action. Thus, the height of flight level is 300m. The probability of flight-out of a predefined flight level is:

$$R=P\{H(FL) - 150 < h(p) > H(FL)+150\}, \tag{13}$$

where $H(FL)$ is a cleared flight level; $h(p)$ is measured barometrical altitude.

Different values of risk are obtained for different PDF used:

$R_{DEPDF}=3.2429\times10^{-9}$;

$R_{TUGED}=7.6883\times10^{-13}$;

$R_{NPDF}=6.7658\times10^{-168}$.

The level of risk values is different according to different tail models used in PDF. NPDF does not have tails thus it gives the lowest value. TUGED and DEPDF include tails, however, their models are different.

6. Conclusions

Maintaining the centerline of cleared flight level is an important component of flight safety. Based on flight level number there is a predefined value of flight level height which guaranty safe airplanes separation. The height of flight level utilizes perils of noise action. Proposed approach helps to identify the risk of vertical separation loss which is a structural component of the entire flight safety at a particular airway connection. During en-route phase of flight a cleared altitude is used. An air traffic control grounds on precise maintenance of this altitude by each airspace user. Airplane flights below or upper than cleared flight level reduce a flight level significantly due to increased risk of mid-air collision with airspace users at the neighbor flight level.

Airplane trajectory data obtained by radio channel from transponder of mode 1090ES under ADS-B are freely distributed with the same level of performance which is available on board. Data processing of historical flights at the unique flight connection makes it possible to measure the risk of particular flight level loss as well as the risk of airplane deviations from cleared flight plan. Both of these risks are the main components of flight safety. ADS-B trajectory data can be used to estimate risks of separations loss by airplane type, by airline, by particular flight connection, by a pilot team, by particular flight route, or by a particular part of airspace. Risk obtained by TUGED PDF can be used to identify navigation and flight technical error distribution, which can be used to find ways of air traffic safety improvements.

References

[1] Yu.Averyanova, A.Rudiakova, F.Yanovsky, Aircraft trajectories correction using sharing operative meteorological radar information, in Proceedings of International Radar Symposium, 9253799, 2020, pp. 256–259

[2] M.Zaliskyi, O.Solomentsev, Method of Sequential Estimation of Statistical Distribution Parameters in Control Systems Design, in Proceedings of 3rd International Conference Methods and Systems of Navigation and Motion Control, IEEE, Kyiv, Ukraine, 2014, pp. 135–138

[3] Aircraft accident and Incident Investigation, Annex 13 to the convention on International Civil Aviation, ICAO, 2016

[4] Safety Report 2021, International Air Transport Association, Geneva, 2022

[5] V.J.Larin,, E.E.Fedorov, Combination of PNN network and DTW method for identification of reserved words, used in aviation during radio negotiation, Radioelectronics and Communications Systems, 57(8), 2014, pp.362–368. DOI: 10.3103/S0735272714080044
[6] O.Solomentsev, M.Zaliskyi, O.Shcherbyna, O.Kozhokhina, Sequential Procedure of Changepoint Analysis During Operational Data Processing, in Proceedings of Microwave Theory and Techniques in Wireless Communications (MTTW), 2020, pp. 168–171
[7] M.Zaliskyi, Yu.Petrova, M.Asanov, E.Bekirov, Statistical Data Processing During Wind Generators Operation, International Journal of Electrical and Electronic Engineering & Telecommunications, 8(1), 2019, pp.33–38
[8] S.Zhyla, V.Volosyuk, V.Pavlikov, N.Ruzhentsev, E.Tserne, A.Popov, Statistical synthesis of aerospace radars structure with optimal spatio-temporal signal processing, extended observation area and high spatial resolution, Radioelectronic and computer systems, 101(1), 2022, pp.178–194
[9] L.Ilnitsky, O.Shcherbyna, F.Yanovsky, Comparison of circular and linear orthogonal polarization bases in electromagnetic field parameters measurement, International Journal of Image, Graphics and Signal Processing (IJIGSP), 14(3), 2022, pp.58–72
[10] I.V.Ostroumov, N.S.Kuzmenko, Statistical Analysis and Flight Route Extraction from Automatic Dependent Surveillance-Broadcast Data, in: Proceedings of the 2022 Integrated Communications Navigation and Surveillance Conference (ICNS), Dulles, VA, USA, 2022, pp. 1-9. DOI:10.1109/ICNS54818.2022.9771515
[11] R.Mori, 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), 2011, pp.30–36. DOI:10.2322/tjsass.54.30
[12] O.A.Sushchenko, Y.N Bezkorovainyi, V.O.Golitsyn, Processing of redundant information in airborne electronic systems by means of neural networks, in Proceedings of 39th International Conference on Electronics and Nanotechnology, IEEE, Kyiv, Ukraine, 2019, pp. 652–655
[13] I.V.Ostroumov, K.Marais, N.S.Kuzmenko, N.Fala, Triple Probability Density Distribution model in the task of Aviation Risk Assessment, Aviation, 24(2), 2020, pp. 57–65. DOI:10.3846/aviation.2020.12544
[14] 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
[15] Yu. Averyanova, E. Znakovskaja, Weather Hazards Analysis for small UASs Durability Enhancement, in Proceedings of 6th International Conference on Actual Problems of Unmanned Aerial Vehicles Development, IEEE, Kyiv, Ukraine, 2021, pp. 41–44
[16] Yu.Averyanova, A.Rudiakova, F.Yanovsky, Drop deformation estimate with multi-polarization radar, Int. Journal of Microwave and Wireless Technologies, 12(9), 2020, pp. 870–877
[17] Air traffic management, Procedures for Air Navigation Services, Doc. 4444, ICAO, 2016
[18] Manual on a 300 m (1 000 ft) Vertical Separation Minimum Between FL 290 and FL 410 Inclusive, Doc 9574, AN/934, ICAO, 2012
[19] Manual of the ICAO Standard Atmosphere: Extended to 80 Kilometres (262 500 Feet). Doc. 7488. ICAO, 1993
[20] A.R.Rodi, D.C.Leon, Correction of static pressure on a research aircraft in accelerated flight using differential pressure measurements, Atmospheric Measurement Techniques, 5(11), 2012, pp.2569–2579
[21] A.G.Holubnychyi, G.F.Konakhovych, A.G.Taranenko, Y.I.Gabrousenko, Comparison of additive and multiplicative complementary sequences for navigation and flight control

systems, in Proceedings of 5th International Conference on Methods and Systems of Navigation and Motion Control IEEE, Kyiv, Ukraine, 2018, pp. 24–27, DOI:10.1109/MSNMC.2018.8576275
[22] V.J.Larin, Development of Measured-Based Feedback on 3-D Coil Non-Invasive Transducer in UAV's Rotation Gear Control Unit, in Proceedings of 3th International Conference on Actual Problems of Unmanned Aerial Vehicles Developments, Kyiv, Ukraine, 2015, pp.270–273
[23] A.H.Holubnychyi, G.F.Konakhovych, Multiplicative complementary binary signal-code constructions, in Radioelectronics and Communications Systems, 61(10), 2018, pp. 431–443
[24] Performance-Based Navigation (PBN) Manual, Doc 9613, ICAO, 2008
[25] I.V.Ostroumov, K.Marais, N.S.Kuzmenko, Aircraft positioning using multiple distance measurements and spline prediction, Aviation 26(1), 2022, pp.1–10. DOI: 10.3846/ aviation.2022.16589
[26] I.V.Ostroumov, N.S.Kuzmenko, Configuration Analysis of European Navigational Aids Network, in: Proceedings of the 2021 Integrated Communications Navigation and Surveillance Conference (ICNS), Dulles, VA, USA, 2021, pp. 1-9. DOI:10.1109/ICNS52807.2021.9441576
[27] O.A.Sushchenko, Y.M.Bezkorovainyi, V.O.Golitsyn, Fault-tolerant inertial measuring instrument with neural network, in Proceedings of 40th International Conference on Electronics and Nanotechnology, Kyiv, Ukraine, 2020, pp. 797–801
[28] O.A.Sushchenko, Y.M.Bezkorovainyi, V.O.Golitsyn, Modelling of microelectromechanical inertial sensors, in Proceedings of 15th International Conference on Experience of Designing and Application of CAD Systems in Microelectronics, Ukraine, 2019, pp. 23–27
[29] V.Larin, N.Chichikalo, K.Larina, A.Shcherban, Algorithm for Processing of Informative and Influencing Factors in UAV Battery Discharge Management System, in Proceedings of 6th International Conference on Actual Problems of Unmanned Aerial Vehicles Developments, Kyiv, Ukraine, 2021, pp.130–134
[30] O.Havrylenko, K.Dergachov, V.Pavlikov, S.Zhyla, O.Shmatko, N.Ruzhentsev, A.Popov, V.Volosyuk, E.Tserne, Decision Support System Based on the ELECTRE Method, Data Science and Security. Lecture Notes in Networks and Systems, 462, 2022, pp. 295–304
[31] M.N.Murty, V.S.Devi, Bayes classifier, Pattern Recognition. Springer, 2011, pp. 86–102