Estimation of horizontal flight efficiency for air traffic management system

Ivan Ostroumov[1] and Nataliia Kuzmenko[1]

[1] National Aviation University, Lubomira Huzara ave., 1, Kyiv, 03058, Ukraine

Abstract
Optimal trajectory selection is one of the common navigation tasks. Air transportation considers horizontal and vertical flight efficiency. Different criteria of trajectory efficiency could be used in algorithms of flight planning: the shortest path, minimization of flight duration, and minimum costs. In air traffic management a portion of additional trajectory length to the shortest path is used as index of horizontal flight efficiency (HFE). In the paper, we study horizontal flight efficiency estimation based on area limited by airplane trajectory and grade circle line. HFE based on area could be useful to indicate the level of side deviation. Results of analysis indicate that a bigger area corresponds to bigger side deviations. Math models of HFE are given in the paper. Validation of considered models of HFE has been done with real trajectory data of particular flight connection, obtained by Automatic Dependent Surveillance-Broadcast technology. A flight connection with a highly inefficient trajectory due to closed airspace caused by the War in Ukraine is considered as an example.

Keywords
Civil aviation, efficiency, navigation, air traffic, statistical analysis, ADS-B

1. Introduction

Civil aviation is one of the key elements in a global transportation system. Air traffic has increased dramatically over the last century [1]. Positive tendency is present in both cargo and passenger traffic over the globe [2]. Today global air transportation shows a clear tendency to recover after COVID-19 action in 2020-2021 [3]. International civil aviation community expects to reach a pre-pandemic level of air transportation at least by 2025[4].

Further growth of the air transportation system requires fundamental changes in airspace structure. Evolution of air space from flight routes to Free route airspace (FRA) is ongoing globally. FRA will significantly increase airspace capacity that gives possibility to integrate new airspace user types with fully autonomous flight capabilities [5, 6]. FRA allows airspace users planning airplane trajectories effectively by any specified trajectory. Many air navigation service providers have already integrated full support of FRA in their airspaces [7].

Airspace usage is planned in advance to ensure the required level of flight safety. Airspace users have to choose the trajectory of upcoming flight as a sequence of waypoints. A set of waypoints forms a flight plan which is submitted to the air traffic management authority. During the validation process, each flight plan is checked to meet multiple criteria of flight safety, including risk of mid-air collision [8]. Only approved flight plans by air traffic management authority could be used to organize air traffic.

Airlines use specific software to plan airplane trajectories based on some criteria of optimality. Minimum flight duration and a minimum of airline cost are the most frequently used criteria for designing a flight route trajectory. Local weather has a significant influence on effective trajectory creation [9, 10]. The majority of flight planning software uses local weather forecasts to have positive input from wind direction and speed. Thus, actual trajectory variation at the unique flight connection is a result of weather action. Also, planed trajectories should avoid entering areas with dangerous weather phenomena action [11, 12]. Accuracy of weather forecasts affects performance of effective trajectories.

ICST-2024: Information Control Systems & Technologies, September 23-25, 2023, Odesa, Ukraine.
ostroumovv@ukr.net (I. Otroumov); nataliiakuzmenko@ukr.net (N. Kuzmenko)
0000-0003-2510-9312 (I. Otroumov); 0000-0002-1482-601X (N. Kuzmenko)

Air traffic management authorities use a horizontal flight efficiency (HFE) index to analyze the level of trajectory efficiency in comparison to the shortest trajectory. HFE is widely used to indicate the possibility of flight routes network to provide efficient trajectory generation [13, 14]. HDE together with vertical flight efficiency index are good indicators of quality of air traffic management in particular airspace volume (sector, area, or region). HFE could be calculated based on flight-planed trajectory (a sequence of waypoints) or by surveillance data.

Primary and secondary surveillance radars are the main localization sensors which are used for air traffic control. Also, automatic dependent surveillance-broadcast (ADS-B) technology is used globally to identify each airspace user location.

ADS-B provides sharing airplane position measured by on-board navigation sensors with other air traffic participants and air traffic control facilities [15, 16]. Easy access to ADS-B surveillance data is provided by numerous commercially available services worldwide [17, 18]. Effective trajectory data processing significantly improves the reliability and safety of airspace usage [19, 20].

In the common case, precision of ADS-B data corresponds to accuracy of the global navigation satellite system used on board as a primary positioning sensor and configuration of the network of ground receivers which are used to receive position reports from airplanes [21, 22]. Also, interference and jamming significantly affect performance of provided data [23, 24].

In the paper, we study calculation of HFE index based on ADS-B data set and develop an error model to estimate a confidence band for HFE. Proposed model is grounded on precision of position data shared by ADS-B technology. A new model of HFE estimation based on the area closed by airplane trajectory and the shortest path is proposed in the paper. Also, we consider the complete trajectory data of a particular flight for HFE analysis.

2. Horizontal flight efficiency

Optimal trajectory depends on criteria that is used for efficient flight connection between two places. In the common case, efficiency connects with the shortest trajectory length. Criteria of short trajectory length work perfectly for automotive and railway vehicles. In air transport, the shortest trajectory length does not give the shortest flight time. Wind distribution along required trajectory is used to move airplane in the most appropriate airflow to get a positive impact into lift force formation. The speed of tailwind is added to airplane air speed and gives additional speed input.

This will result in the amount of required fuel for the whole flight and finally will reduce flight cost. Also, headwind reduces airplane speed due to increasing resistance.

Wind triangle equation is used to calculate ground speed (AGS) of airplane based on airspeed (AS) and wind speed (WS):

$$AGS = \sqrt{AS^2 - 2WSAS\cos(H + 180 - W) + WS^2}\,, \tag{1}$$

where H is an airplane heading; W is wind speed.

Weather forecast services provide easy access to wind speed data at different atmospheric layers. Flight planning software uses wind data to get maximum input from tailwinds based on (1) during the whole flight trajectory. However, during the actual flight weather data could be different a little bit from forecasted values which introduces a bias in effective trajectory variation.

Collaborative analysis of airplane trajectory and wind parameters distribution along the trajectory in post-flight mode helps to get an index of effective trajectory.

In practical implementation, HFE index calculation based on weather distribution is complicated.

Weather fluctuation does not provide a stable response to trajectory geometry. Therefore, HFE is calculated based on trajectory length only.

The shortest path between two points located on a spherical surface is an arch length of the Great Circle (GC) that connects both points:

$$L = \mathrm{D}\, asin\sqrt{sin^2\left(\frac{\varphi_\mathrm{B} - \varphi_\mathrm{A}}{2}\right) + cos(\varphi_\mathrm{A})cos(\varphi_\mathrm{B})sin^2\left(\frac{\lambda_\mathrm{B} - \lambda_\mathrm{A}}{2}\right)}, \tag{2}$$

where D is the diameter of the Great Circle line; λ_A and φ_A are geocentrical coordinates of latitude and longitude of point A; λ_B and φ_B are coordinates of point B.

HFE does not consider airplane variation in vertical profile. Thus, length variation due to climbing and descending is not used.

Actual airplane trajectory fluctuates along GC line to follow flight route network configuration and wind forecast used at the time of flight planning (Figure 1).

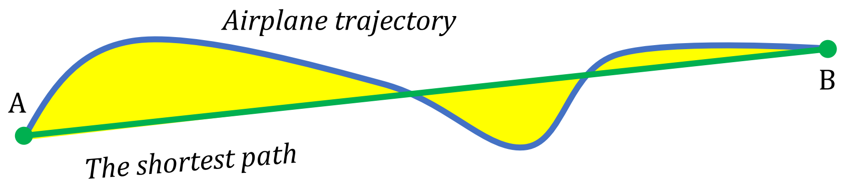

Figure 1: Variation of actual airplane trajectory in relation to GC

HFE index is calculated as a percentage of additional trajectory length to total GC length. It shows how many additional units of length are added to each unit of GC line:

$$HFE = \frac{\sum_{i=1}^{n-1} D_i - L}{L}, \quad (3)$$

where L is the length of GC line; D_i is the length of i-th leg of airplane trajectory; n is the number of trajectory data.

Total trajectory length (D) is calculated as a sum of each leg. Length of each leg is calculated as a GC line as well. In case the length is small enough, it is calculated as a direct distance between two points.

Due to exactly known location of start point A and endpoint B, we assume that arch-length of GC line (L) is known precisely. However, airplane trajectory data is measured by on-board positioning system with a particular level of precision.

Precision of trajectory data is available in ADS-B messages as navigation accuracy category (NAC). There are 11 levels of NAC, each of them often corresponds to particular positioning accuracy. NAC is transmitted in specific data messages that indicate the operational status of system. In case precision of positioning is available in NAC, a confidence band in 95% could be used:

$$2\sigma_{HFE} = 2\text{NAC}. \quad (4)$$

Boundary levels of $\pm 2\sigma_{HFE}$ is used to specify a confidence band 95% along the HFE line.

In a global satellite navigation system precision could be specified as two components: standard deviation error on the North-South side (σ_N) and standard deviation error in the West-East side (σ_E)[25]. In scenario if σ_N and σ_E are given for each data point, then a Taylor series expansion by the first level of derivatives could be used to get σ_{HFE}:

$$\sigma_{HFE} = \frac{dHFE}{dx}\sigma_N + \frac{dHFE}{dy}\sigma_E \quad (5)$$

where $\frac{dHFE}{dx}$ is a partial derivative from (3) in the North direction; $\frac{dHFE}{dy}$ is a partial derivative from (3) on the East side.

Values of σ_N and σ_E are simulated by GNSS error distribution over the globe by one of the scenarios of particular constellations.

Estimation of HFE by additional trajectory length indicates only total trajectory inefficiency. An area index could be useful to show trajectory deviation from the shortest path. An area closed by actual airplane trajectory and the shortest path could be a good indicator of trajectory variation along the GC line.

A comparison of two trajectories variations by area index is shown in Figure 2.

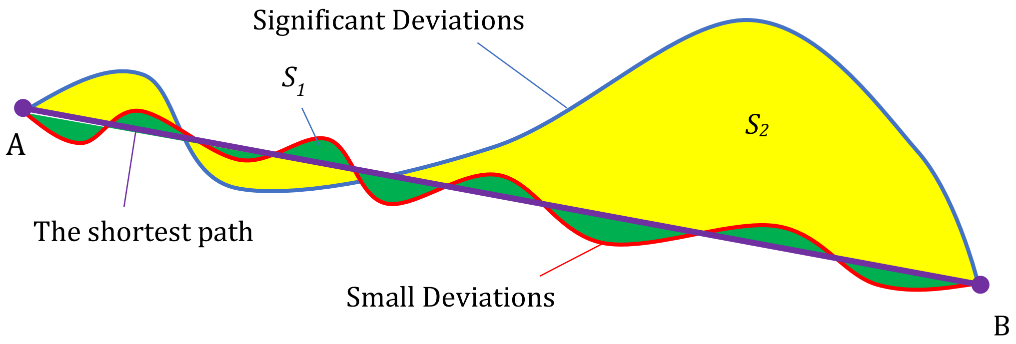

Figure 2: Comparison of two trajectory variations by area index

The small area index indicates trajectory fluctuation closer to the shortest path. A bigger area index means that significant deviations are present.

The area could be calculated by one of the numerical methods: rectangular, trapezia or Simpson formula. As input data for calculation, a GC line should be discretized into a set of points which are reference points for normal from GC to each trajectory data. Coordinates of normal base could be calculated as follows in local cartesian North-East (NE) reference frame:

$$x_i = \frac{x_A(y_B-y_A)^2+X_i(x_B-x_A)^2+(x_B-x_A)(y_B-y_A)(Y_i-y_A)}{(y_B-y_A)^2+(x_B-x_A)^2},$$
$$y_i = Y_i + \frac{(x_B-x_A)(X_i-x_A)}{y_B-y_A}, \quad (6)$$

where x_A and y_A are coordinates of start point in NE; x_B and y_B are coordinates of the endpoint in NE; X_i and Y_i are coordinates of the i-th data point of airplane trajectory.

A set of lengths between points in GC line (h_i) should be calculated:

$$h_i = \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2}. \quad (7)$$

Length of perpendicular line (p_i) from each trajectory point to GC line is calculates as follows:

$$p_i = \sqrt{(X_i-x_i)^2 + (Y_i-y_i)^2 - h_i^2}. \quad (8)$$

Finally, an area could be estimated by trapezia method of numerical integration:

$$S = \frac{1}{2}\sum_{i=1}^{n-1} h_i(p_i + p_{i+1}), \quad (9)$$

where *n* is the number of trajectory points.

Trapezia method of area estimation shows good precision with increased number of iterations. In case if input data set is not synchronized and includes multiple gaps, the data interpolation could be used to obtain the required number of input points to calculate the area precisely [26].

3. Trajectory data

Trajectory data in air traffic management are obtained from a group of surveillance sensors. Secondary and weather radars are the primary localization equipment used in civil aviation to measure airspace users' location. Multilateration systems are used in the terminal airspace of airports to sense airplane position. Also, the ground network of ADS-B receivers is used by air navigation service providers to collect the position of each airplane measured onboard. Also, there are multiple commercially available databases that process ADS-B messages all over the globe and provide easy access to collections of historical flights based on the identification code of airplanes. Trajectory data from radars and multilateration systems are synchronized in time. ADS-B data is based on data transferred in a digital data channel from onboard equipment of an airplane. It grounds on 1090MHz frequency band. Because of non-control access to the channel, some messages could be overlapped, that causes the loss of all transferred data. Interference action is a common problem of ADS-B which is significant in congested airspace. Broken messages cause appearance gaps in the sequence of data. Also, a configuration of ground receivers network may be limited by the maximum range of wireless communication, that caused long periods of data absence.

For example, trajectory data from airplanes over the ocean airspace could be unavailable because of the lack of ground facilities. Thus, trajectory data available from ADS-B services is not synchronized.

Analysis of HFE requires to have a full sequence of data points in airplane trajectory. Holes in data caused simple linear approximation between available data.

The performance of HFE could be improved by using some algorithms of data recovery to fill the gaps in the data series. In case of post-flight data processing, methods of data interpolation by regression could be useful. Spline functions could be used as a regression function to provide precise data fitting.

A basis function of B-Spline is estimated as follows:

$$F_{i,j}(x) = \frac{\tau_{i+j}-x}{\tau_{i+j}-\tau_{i+1}} F_{i+1,j-1}(x) + \frac{x-\tau_i}{\tau_{i+j-1}-\tau_i} F_{i,j-1}(x)\ , \qquad (10)$$

where j is function order; τ is a knot vector.
Spline functions form a basis matrix for regression:

$$B = \begin{bmatrix} F_{1,j}(x_1) & \dots & F_{m,n}(x_1) \\ \vdots & \ddots & \vdots \\ F_{1,j}(x_m) & \dots & F_{m,n}(x_m) \end{bmatrix}, \qquad (11)$$

where m is the total number of data points available in ADS-B trajectory; n is the number of knots; x is available data.

Based on input trajectory data a sequence of control points (C) could be calculated as follows:

$$C=(B^TB)^{-1}B^TX, \qquad (12)$$

where X is available trajectory data by one flight realization.

Finally, recovered trajectory data could be estimated for any required time series based on control points (C) and basis matrix (B):

$$Y=BC. \qquad (13)$$

Spline function provides a good fitting of trajectory data. It also could be used to recover a fully synchronized time series from raw ADS-B data input in pot processing mode.

For the case of real-time system operation, the trajectory filters could be used for data extrapolation. In most cases, the performance of air traffic management is analyzed in a post-processing mode.

4. Numerical demonstration

A trajectory data of real air traffic is used to analyze HFE. We use trajectory data of AAL 292 flight operated by American Airlines for flight connection between J.F. Kennedy (New York, USA, KJFK) and Indira Gandhi (New Delhi, India, VIDP) international airports. Trajectory data was collected by the network of ground-based ADS-B receivers.

The data set includes 45 unique flight realizations between April 16 and May 31, 2024. Each trajectory is specified as a sequence of points in geodetic coordinates of latitude, longitude, and altitude, accompanied with a synchronized timestamp.

Because of the war in Ukraine, the airspace of russian federation and Ukraine have been limited to use [27, 28]. It caused flight AAL 292 to deviate significantly from the GC line to avoid entering a risky airspace.

Trajectory variation for 45 one-side flights of AAL 292 are presented in Figure 3. Also, airspaces of some countries in the Middle East region are also limited due to the high risk of military action, that also affects trajectory variation of AAL 292.

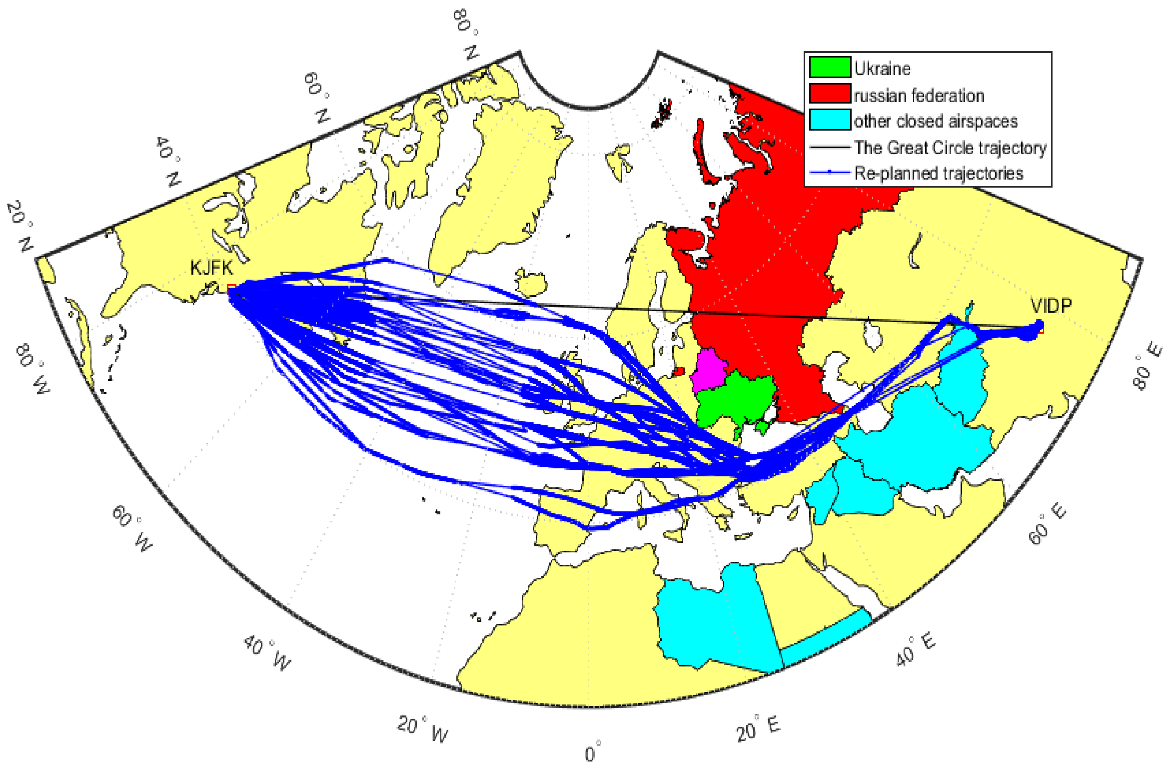

Figure 3: Trajectory variation of AAL 292 during April 16 - May 31, 2024

Trajectory length variation calculated by (2) for the input sequence of trajectory data points is shown in Figure 4.

Mean value of total trajectory length is 13.2×103 km. Additional trajectory length variation in comparison to GC length is shown in Figure 5.

Due to significant variation in total trajectory length, a standard deviation in total time of flight is only 12 min. Mean total time of flight is 12:10. Histogram of total time of flight variation is shown in Figure 6.

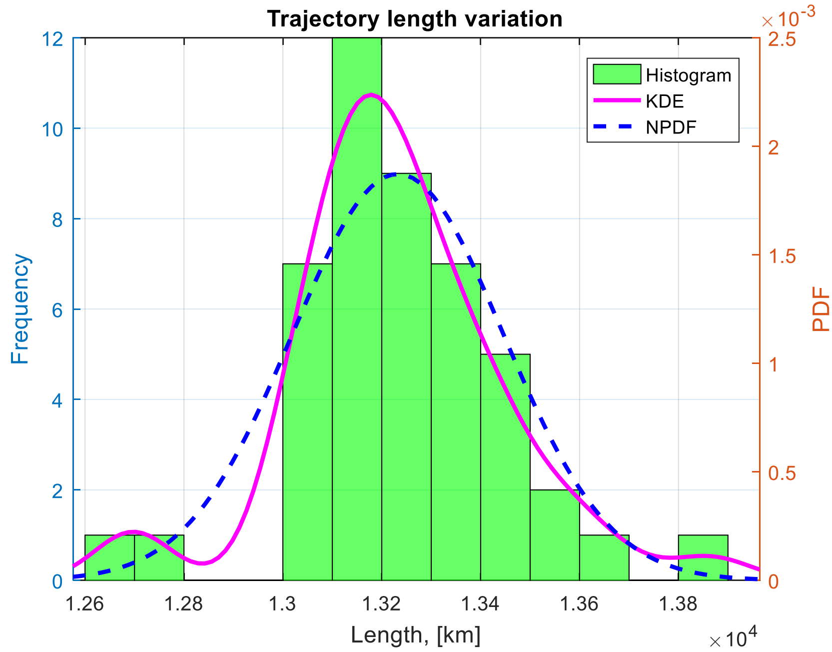

Figure 4: Trajectory length variation of AAL 292

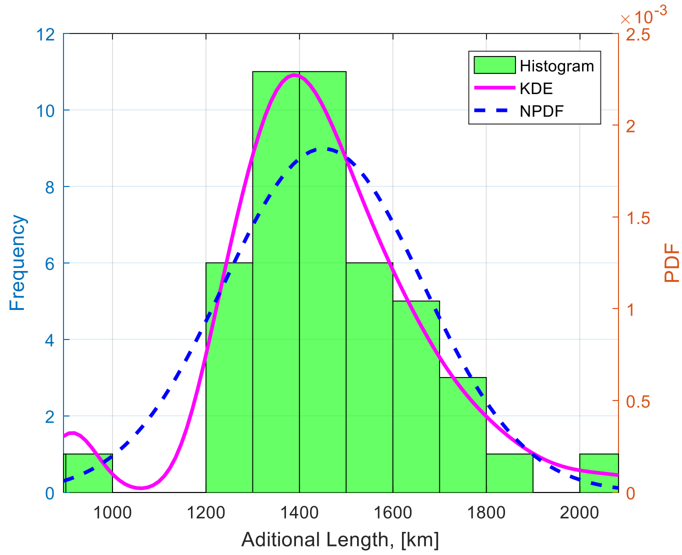

Figure 5: Additional trajectory length variation to GC line

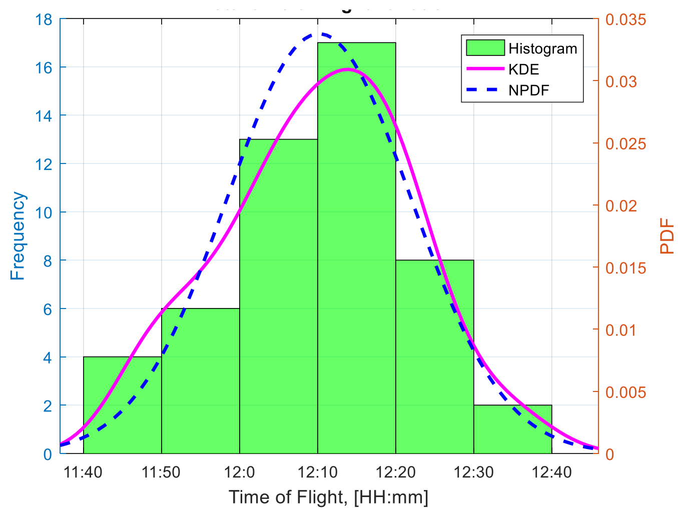

Figure 6: Flight duration variation for AAL 292

For each flight realization a HFE in length and area are calculated by (3) and (8) correspondently. Results are shown in Figure 7 and Figure 8

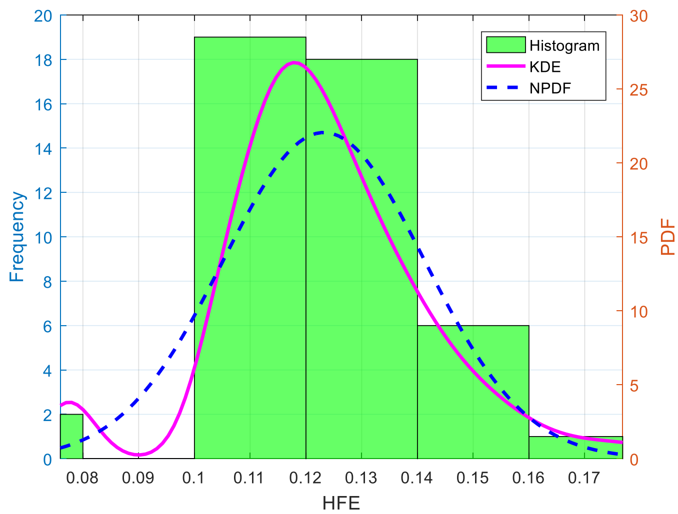

Figure 7: Variation in HFE for AAL 292 calculated by (3)

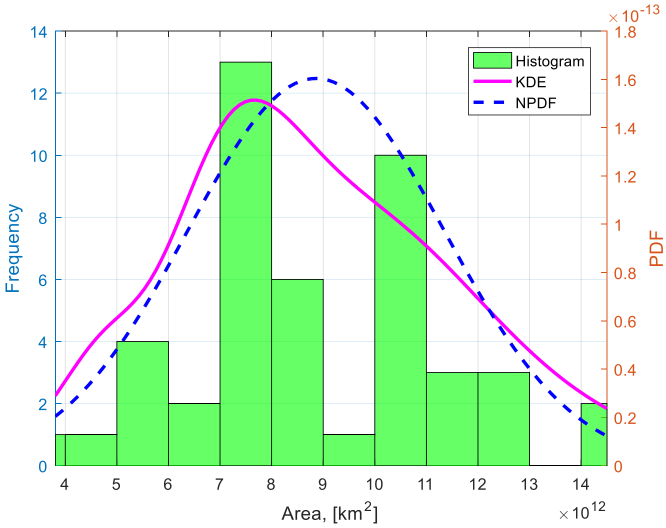

Figure 8: Variation in area of HFE for AAL 292 calculated by (8)

In statistical data analysis we estimate a probability density function of particular distribution. A normal probability density function (NPDF) gives average results. Results of fitting a Kernel probability density function (KPDF) to input statistic gives better performance. Estimated probability density functions by input data set could be useful to estimate a confidence bands of particular parameter. A confidence band in 95 % is most frequently used in civil aviation.

A longer non-stop flight with long length of total trajectory makes HFE small enough. For short flight connections HFE is significantly bigger, due to lower length of GC line.

HFE based on additional length and area could be used together to make precise description of trajectory efficiency level. A simple correlation study of both indexes helps to classify effective trajectory based on level of deviation from mean values for multiple realization of particular flight connection. The correlation of HFE and area is shown in Figure 9.

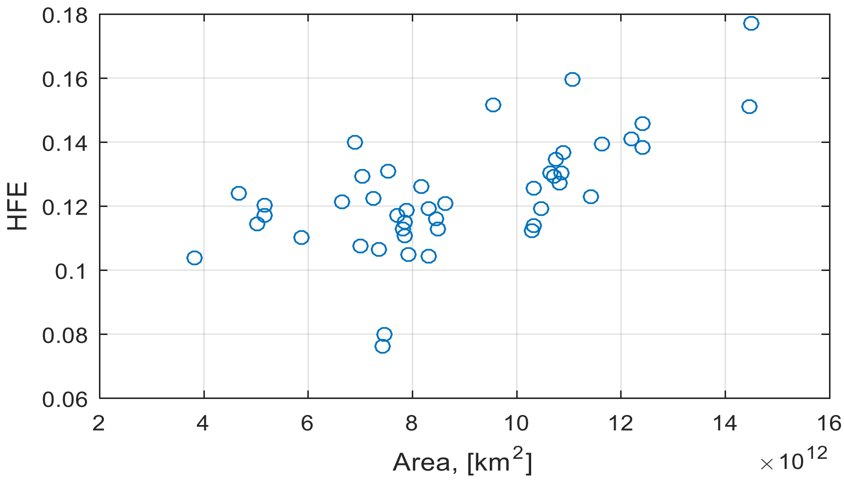

Figure 9: Correlation of area and HFE for AAL 292

Deviation of values in Figure 9. from the diagonal line indicates about presence of excessive side deviation. In the most cases it corresponds to bigger value of area and a lower value of additional length.

Conclusions

Horizontal flight efficiency is a key indicator of effective air traffic management in particular airspace volume. A portion of additional trajectory length to the shortest path is a good indicator of HFE. HFE based on area of airspace limited by trajectory line and great circle line is useful to analyze the level of side deviations. Also, a correlated analysis of both indexes is a great indicator of airplane side deviation from the great circle line.

Both models of HFE indicate the importance of their usage in the tasks of post-flight trajectory analysis. Trajectory analysis of multiple realizations of one side flight connection with HFE helps to identify factors affecting the trajectory deviations from the great circle line. Also, it helps to find a decision on minimization of factors action to increase HDE for particular flight connection and increase flight safety as well.

Trajectory of AAL 292 flight has big variation during considered period from April 16 - May 31, 2024 which result in significant total length variation. Well-planned trajectory based on positive weather input gives minimization of total flight time at the point of 12:10 with a standard deviation of 12 min only. Trajectory analysis in the post-flight mode based on ADS-B data set could be useful for air traffic authorities to increase efficiency of airspace usage.

Acknowledgment

This project has received funding through the EURIZON project, which is funded by the European Union under grant agreement No.871072. (Project EU #3035 EURIZON "Research and development of Ukrainian ground network of navigational aids for increasing the safety of civil aviation").

References

[1] Effects of Novel Coronavirus (COVID 19) on Civil Aviation: Economic Impact Analysis. ICAO, 2022. URL: https://www.icao.int/sustainability/Pages/Economic-Impacts-of-COVID-19.aspx.

[2] European ATM Master Plan, SESAR JU, 2020. URL: https://www.sesarju.eu/masterplan.

[3] X. Bao, P. Ji, W. Lin, M. Perc, J. Kurths, The impact of COVID-19 on the worldwide air transportation network, Royal Society open science 8(11) (2021) 210682. doi: 10.1098/rsos.210682.

[4] Performance Review Report. An assessment of Air Traffic Management in Europe during the calendar year 2023. Eurocontrol, 2024. URL: https://www.eurocontrol.int/publication/performance-review-report-prr-2023-consultation.

[5] C. Nava–Gaxiola, C. Barrado, P. Royo, Study of a Full Implementation of Free Route in the European Airspace, in: 37th Digital Avionics Systems Conference (DASC), IEEE/AIAA, London, UK, 2018, pp. 1–6. doi: 10.1109/DASC.2018.8569543.

[6] I.V. Ostroumov, V.P. Kharchenko, N.S. Kuzmenko, An airspace analysis according to area navigation requirements, Aviation 23(2) (2019) 36–42, doi: 10.3846/aviation.2019.10302 .

[7] H. Hirabayashi, M. Brown, N. Takeichi, Feasibility study of free routing airspace operation over the North Pacific airspace, in: Fourteenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2021), 2021, pp. 20–23.

[8] I. Ostroumov, N. Kuzmenko, Risk Assessment of Mid-air Collision Based on Positioning Performance by Navigational Aids, in: 6th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC), Kyiv, Ukraine, 2020, pp. 34–37. doi: 10.1109/MSNMC50359.2020.9255506.

[9] C. Ramee, J. Kim, M. Deguignet, C. Justin, S. Briceno, D. Mavris, Aircraft flight plan optimization with dynamic weather and airspace constraints, in: Proceedings of the international conference Res. Air Transp., 2020, pp. 1–8.

[10] M. Selecky, P. Vana, M. Rollo, T. Meiser, Wind corrections in flight path planning, International Journal of Advanced Robotic Systems 10(5) (2013) 248. doi: 10.5772/56455.

[11] A. Popov, E. Tserne, V. Volosyuk, S. Zhyla, V. Pavlikov, N. Ruzhentsev, Invariant Polarization Signatures for Recognition of Hydrometeors by Airborne Weather Radars, in: O. Gervasi, B. Murgante, D. Taniar, B. Apduhan, A. Braga, C. Garau, A. Stratigea (Eds.), Computational Science and Its Applications, ICCSA 2023, volume 13956 of Lecture Notes in Computer Science, Springer, Cham, 2023, pp. 201–217. doi: 10.1007/978-3-031-36805-9_14.

[12] Y. Averyanova, V. Larin, M. Zaliskyi, O. Solomentsev, Turbulence Detection and Classification Algorithm Using Data from AWR, in: 2nd Ukrainian Microwave Week (UkrMW), Ukraine, 2022, pp. 518–522. doi: 10.1109/UkrMW58013.2022.10037172.

[13] L. Leones, P. Morales, M. D'Alto, L. MacNamee, B. Wang, S. Grover, et al., Advanced Flight Efficiency Key Performance Indicators to support Air Traffic Analytics: Assessment of European flight efficiency using ADS-B data, in: 37th Digital Avionics Systems Conference (DASC), IEEE/AIAA, London, UK, 2018, pp. 1–10, doi: 10.1109/DASC.2018.8569584.

[14] O. Solomentsev, M. Zaliskyi, O. Zuiev, Estimation of Quality Parameters in the Radio Flight Support Operational System, Aviation 20(3) (2016) 123–128. doi: 10.3846/16487788.2016.1227541.

[15] D. Yun, Y. Yong, X. Kaijun, X. Zhaoyu, Progress of ADS-B IN technology in civil aviation applications, in: 7th International Conference on Communication, Image and Signal Processing (CCISP), Chengdu, China, 2022, pp. 1–5. doi: 10.1109/CCISP55629.2022.9974442.

[16] O. Holubnychyi, M. Zaliskyi, O. Sushchenko, O. Solomentsev, Y. Averyanova, Self-Organization Technique with a Norm Transformation Based Filtering for Sustainable Infocommunications Within CNS/ATM Systems, in: Zaliskyi, M. (eds) Proceedings of the 2nd International Workshop on Advances in Civil Aviation Systems Development. ACASD 2024, volume 992 of Lecture Notes in Networks and Systems, Springer Cham, 2024, pp. 262–278. doi: 10.1007/978-3-031-60196-5_20.

[17] OpenSky, The OpenSky Network, 2024. URL: https://opensky-network.org.

[18] Flightaware. URL: https://www.flightaware.com.

[19] O. Solomentsev, M. Zaliskyi, O. Kozhokhina, T. Herasymenko, Efficiency of data processing for UAV operation system, in: 4th International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD), Kyiv, Ukraine, 2017, pp. 27–31. doi: 10.1109/APUAVD.2017.8308769.

[20] M. Zaliskyi, O. Solomentsev, O. Kozhokhina, T. Herasymenko, Reliability Parameters Estimation for Radioelectronic Equipment in Case of Change-point, in Signal Processing Symposium 2017 (SPSympo 2017), Jachranka Village, Poland, September 12-14, 2017, pp. 1–4. doi: 10.1109/SPS.2017.8053676.

[21] J. Sun, The 1090 megahertz riddle: a guide to decoding mode S and ADS-B signals. TU Delft OPEN Publishing, 2021.

[22] K. Dergachov, O. Havrylenko, V. Pavlikov, S. Zhyla, E. Tserne, V. Volosyuk, GPS Usage Analysis for Angular Orientation Practical Tasks Solving, in: 9th International Conference on Problems of Infocommunications, Science and Technology (PIC S&T), IEEE, Kharkiv, Ukraine, 2022, pp. 187–192. doi: 10.1109/PICST57299.2022.10238629.

[23] S. Pleninger et al., Jamming of GNSS Receiver on B737 MAX Aircraft and Its Impact on ADS-B Technology, in: New Trends in Civil Aviation (NTCA), Prague, Czech Republic, 2020, pp. 123–128. doi: 10.23919/NTCA50409.2020.9290995.

[24] I. V. Ostroumov, N. S. Kuzmenko, An Area Navigation (RNAV) System Performance Monitoring and Alerting, in: First International Conference on System Analysis & Intelligent Computing (SAIC), Kyiv, Ukraine, IEEE, 2018, pp. 1–4. doi: 10.1109/SAIC.2018.8516750.

[25] R. Voliansky, O. Sushchenko, Y. Averyanova, O. Solomentsev, O. Holubnychyi, and M. Zaliskyi, Variable-Structure Interval-Based Duffing Oscillator, in 42nd International Conference on Electronics and Nanotechnology (ELNANO), IEEE, Kyiv, Urkaine, 2024, pp. 581–586.

[26] I.V. Ostroumov, N.S. Kuzmenko, Accuracy improvement of VOR/VOR navigation with angle extrapolation by linear regression, Telecommunications and Radio Engineering 78(15) (2019) 1399–1412. doi: 10.1615/TelecomRadEng.v78.i15.90.

[27] C. Chu, H. Zhang, J. Zhang, L. Cong, F. Lu, Assessing impacts of the Russia-Ukraine conflict on global air transportation: From the view of mass flight trajectories. Journal of Air Transport Management 115 (2024) 102522. doi: 10.1016/j.jairtraman.2023.102522.

[28] V. Ivannikova, O. Sokolova, K. Cherednichenko, How the War in Ukraine Impacts Global Air Transportation Ecosystem: Assessment and Forecasting of Consequences, in: International Conference TRANSBALTICA: Transportation Science and Technology, 2023. Cham: Springer Nature Switzerland, pp. 386–401. doi: 10.1007/978-3-031-52652-7_38.