Evaluation of the probability of the aircraft going beyond the lateral limits of the route for the airspace of Turkey

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Abstract

The risk of aircraft collision in the air is the most dangerous phenomenon in aviation. In connection with the growing air flow to Turkey, this risk cannot be underestimated. In this study, a calculation of the probability of the aircraft going beyond the established route will be made based on the static analysis of the data regarding the flight of the aircraft along the routes. The data were collected using Automatic Dependent Surveillance-Broadcast (ADS-B) transmitters and then processed in the Python programming environment. The risk is calculated using the probability density function as the area under the function bounded by the lateral boundaries of the route.

Keywords

airplane, separation, navigation, risk, routes, ADS-B, lateral deviation, probability density function, big data

1. Introduction

The world is currently in a very difficult period when many military conflicts are arising across the globe. It affected every sphere of the economy at different levels, and aviation was no exception. In its annual report for 2023, the International Air Transport Association (IATA) [1] indicated that the aviation industry had just recovered from the covid-19 pandemic, as they were challenged by new problems, starting with a large-scale earthquake in Turkey and Syria, as well as the war in Ukraine and its impact on the global economy and politics. But we should not forget about the old problems associated with the limited volume of air space and the accompanying problem with the risk of collision [2, 3, 4]. Of course, the main cause of such an event is an error on the part of the dispatcher or pilot, or a technical malfunction, although, in the current concept of risk management, such an event is possible only if there is a problem or shortcomings in the above-mentioned parties [5]. The dispatcher, as a person whose task is to warn and prevent the occurrence of emergency and catastrophic events, is under a load, operating many planes at the same time, that can lead to mistakes. Also, the volume of air transportation is constantly increasing with the number

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of planes increasing [6]. However, the volume of airspace in which they fly and which the controller operates remains unchanged, so the risk of collision increases.

Turkey has always had an advantageous position as a bridge between Europe and Asia. At the moment, this position has only been consolidated, because due to the Russian invasion of Ukraine, many Western countries have imposed sanctions on Russia, including the aviation industry. Because of this, the main air flow from Europe to Asia now passes through Turkey [7, 8, 9]. This, in turn, brings us back to the main problem of the study, because the volume of Turkish airspace remains unchanged, while the traffic in the absence of alternatives grows.

The lack of air space arises because of the concept of air space construction, as planes fly on predetermined routes. One of the options for solving the problem is the transition to an alternative concept, which is currently being actively implemented in European countries, Free Route Airspace (FRA) [10], according to which airspace users themselves choose how to fly in the airspace and are not limited only by routes. Thus increasing the volume of airspace available for use, although there remain a number of problems arising from the implementation of such a concept related to the organization of traffic on the border between the FRA application area and the area without it, as well as with security due to the increase of potential conflict points. According to the plans of Eurocontrol, by 2025, FRA will be applied 24/7 in almost all the space belonging to the member countries of the organization, both in the lower and upper airspace.

The problem of the collision of planes in the air has been studied for many years, because this is the most deadly event that can happen in aviation. Therefore, to determine the risk, there is a collision risk model (CRM) that calculates the probability of a collision. To calculate the CRM in the horizontal plane, the ICAO uses Reich mode, which represents the plane as a box whose parameters are equal to the echelon minimums, therefore, if there is an overlap of the area of the boxes of two different planes, this indicates a violation of the minimums and, accordingly, the risk of an increase in the risk of collision [11]. But in order to calculate this risk, it is first necessary to determine the probability of deviation of the plane from the center of the route along which it flies. The probability of deviation can be calculated using static data processing with the probability density function [12, 13].

In the paper a specialized software is developed for automatic safety level detection based on airplane trajectory input.

2. Air traffic flow and separation

Airspace is a designated volume of the atmosphere that is under the control of a certain state, and this is the part that is above its land territories and territorial waters. For the convenience of organizing air traffic, airspace is divided into controlled and uncontrolled. Controlled is the one where dispatching service is provided. Uncontrolled is the one where dispatching service is not provided. In addition, the airspace can be divided into upper and lower echelon 275 (8400 m). Moreover, in order to divide the areas of management and responsibilities of various dispatching services, the airspace is divided into the following elements: Control Area (CTA), Terminal Control Area (TMA), Control Zone (CTR), Flight Information Region (FIR), Flight Information Zone (FIZ), Aerodrome Flight Information

Zone (AFIZ) and Aerodrome Traffic Zone (ATZ). ICAO also applies a special classification of airspace (seven classes from A to G) to determine which dispatching service to apply and what are the requirements for airspace users in this class [14]. There are also special types of flight zones in which flights are prohibited or restricted for some reason. So, a dangerous zone is a defined volume of airspace where an event dangerous to aviation can occur at a certain time (artillery fire, fireworks, or natural disasters such as forest fires or volcanic eruptions). A prohibited zone is a flight in which it is unacceptable for civil aviation under any circumstances and at any time (airspace over nuclear power plants, military and state strategic objects, etc.). The last is a limited zone where civil aviation flight is possible subject to certain conditions, such as meteorological or time.

The dispatching authority of the respective country is responsible for the organization of air traffic. The controller's task is to provide safe, economical and effective air traffic control. To perform this task, the dispatcher uses the most important tool at his disposal - separation. Separationing is vertical and horizontal (the latter is divided into longitudinal and lateral separationing. It should also be said that there is separationing by time and by distance (we will consider the latter during the study). Vertical separationing has two values: 300 m for aircraft flying up to 290 FL and for aircraft permitted to fly in the zone of reduced vertical separation minima (RVSM) between 290 and 410 FL (excluding government aircraft) and 600 m for all aircraft flying above 290 FL and which are not permitted to fly in RVSM. Horizontal separationing depends on the navigational aids used and the navigational methods. The width of the route along which the aircraft flies is also determined by the navigational aids. If we are talking about the zonal navigation method (RNAV), then the aircraft can fly not from one radio beacon to another, but it must be able to fly in the center of the determined route during 95% of the flight [15]. However, due to a number of factors, it was decided to improve the method of area navigation to the method of navigation by characteristics so that the main navigation characteristics were expressed in accuracy, integrity, continuity, and functionality. The most common navigation characteristics at the moment are:

- RNAV 10 for oceanic routes, route width 50 NM;
- RNAV 5 for en-route leg routes, route width 5 NM;
- RNP 4 for oceanic routes, route width 23 NM;
- RNP 1 for the approach/takeoff phase, route width 1 NM.

There are different types of routes. When talking about the route of the airspace, we are talking about a clearly defined segment of airspace that is used to direct the flow of airships. In a general sense, it combines all types of air routes:

- Advisory service is performed in uncontrolled airspace, where advisory service is provided;
- An uncontrolled route is also in uncontrolled airspace, but only emergency service is provided;
- Controlled is the one on which dispatching service is provided.

Air routes that will be described later will be the last type of control. Because it is on them that commercial aviation makes flights.

3. Probability density function of airplane lateral deviation

We use static and analytical research methods to obtain results, as well as the Python programming environment and probability density function to obtain the probability of the aircraft leaving the set limits. At, the first step to be taken is to collect data on the movement of aircraft over the territory of Turkey using the Python software environment and additional libraries. The data is obtained from Automatic dependent surveillance-broadcast (ADS-B) transmitters, which are an element of Communication, Navigation, Surveillance (CNS) of aviation, which refers to surveillance in the same way as primary, and secondary radars. ADS-B get location of the aircraft from global navigation satellite systems (GNSS), and transmits this data not only to ground stations (which include dispatchers) but also to nearby airships [16]. The collected data were transferred to a single coordinate system for further calculations. Any data that go beyond the borders of Turkey were rejected.

To calculate the deviation of the plane from the center of the route, we used the level of a straight line. Having two points: the beginning and the end of the route get the equation of the straight line passing through them:

$$ax + by + c = 0, \quad (1)$$

where *(x, y)* are the coordinates of the point, *a, b, c* are free changes that we will get in the following way:

$$(y_2 - y_1)x - (x_2 - x_1)y - 2x_1y_2 = 0, \quad (2)$$

where (x_1, y_1) are the coordinates of the first point on the route segment, (x_2, y_2) are the coordinates of the segment end.

Solving equation (2), we get the values of *a,b,c*. After drawing a perpendicular from the straight route, at the point of its intersection with the curve of the plane's trajectory, from the obtained point to the base of the perpendicular, there will be a deviation of the plane. And so on for each subsequent point along the selected route. The distance itself can be calculated as follows:

$$d = \frac{ax_i + by_i + c}{\sqrt{a^2 + b^2}}, \quad (3)$$

where *a, b, c* are free to change what we got from (2), for the route to which the coordinates of the flight curve (x_i, y_i) correspond.

Now we need to use the probability density function (PDF) $\rho(x)$, since the resulting sample will be discrete, that is, we will not be able to accurately estimate the risk of the plane going beyond the set limits. Therefore, we need a continuous sample of flights that can include the completeness of information that compensates for the limited amount of received data. PDF will be able to calculate the probability of deviation as a value that exceeds the set limit (route width) (Figure 1) [17].

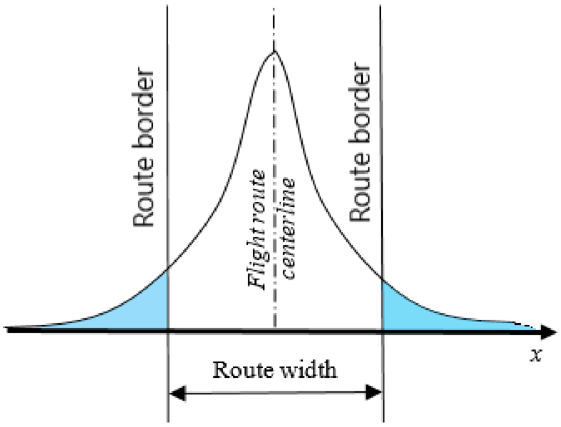

Figure 1: PDF of airplane lateral deviation.

We can calculate the risk of the aircraft going off-route as follows:

$$R = \int_{-\infty}^{-l} \rho(x)dx + \int_{\infty}^{l} \rho(x)dx, \tag{4}$$

or

$$R = 1 - \int_{-l}^{l} \rho(x)dx, \tag{5}$$

where l is a separation minimum.

As a PDF a Normal (ND), Exponential (ED), Double Exponential (DED), or Univariate Generalized Error Distribution (UGED) can be used. In our research we use ND with a next form [18]:

$$\rho(x) = \frac{1}{2^{k+1}\sigma\Gamma(k+1)} exp\left(-\frac{1}{2}\left|\frac{x-\mu}{\sigma}\right|^{\frac{1}{k}}\right), \tag{6}$$

where σ is the dispersion of the distribution; k is a controls the skewness; μ is a mode of the distribution; Γ(k+1) is an Eelier-gamma function.

The flexibility of UGED makes ρ(x) similar to ND if *k*=0.5 and to DED in case *k*=1.

It should also be noted that the probability of lateral deviation of the aircraft is used in the calculation of the Reich collision risk model, which is the basis of the TLS indicator implemented by the ICAO for calculating safety. It shows what should be the number of plane crashes in a certain airspace per hour. It has been officially established that this value should be equal to 5×10^{-9}, therefore, for the services responsible for air navigation, any TLS for their sector of responsibility with a value smaller than the established value is considered acceptable. The value of the risk according to the Reich model [11] is calculated as follows:

$$N_{ax} = 2\Pi_x P_y(0) P_z(0)\left(\frac{\overline{|\dot{x}(m)|}}{2\lambda_x} + \frac{\overline{|\dot{y}_0|}}{2\lambda_y} + \frac{\overline{|\dot{z}_0|}}{2\lambda_z}\right), \tag{7}$$

where $\overline{|\dot{y}_0|}$ is the average transverse speed of the aircraft on the route; $\overline{|\dot{z}_0|}$ is the average vertical speed of the aircraft on the route; $|\dot{x}(m)|$ is the average lateral speed of the aircraft on the route; *m* is the minimum echelon on the route; $\lambda_x, \lambda_y, \lambda_z$ are length, width, and height of the aircraft model; Π_x is probability of lateral overlap; $P_z(0)$ is probability of vertical overlap; $P_y(0)$ is probability of transverse overlap.

4. Risk estimation of lateral deviation in Turkey airspace

Software has been developed in Python programming language using installed selenium library. On May 22-23, 2024, records of about 165 flights from the 10 largest airports in Turkey were obtained: IST, AYT, ESB, ADB, DLM, ADA, BJV, TZX, and GZT. As mentioned earlier, all data coordinates, whose coordinates go beyond the airspace of Turkey, were discarded, and the obtained results were visualized using OpenStreetMap Figure 2.

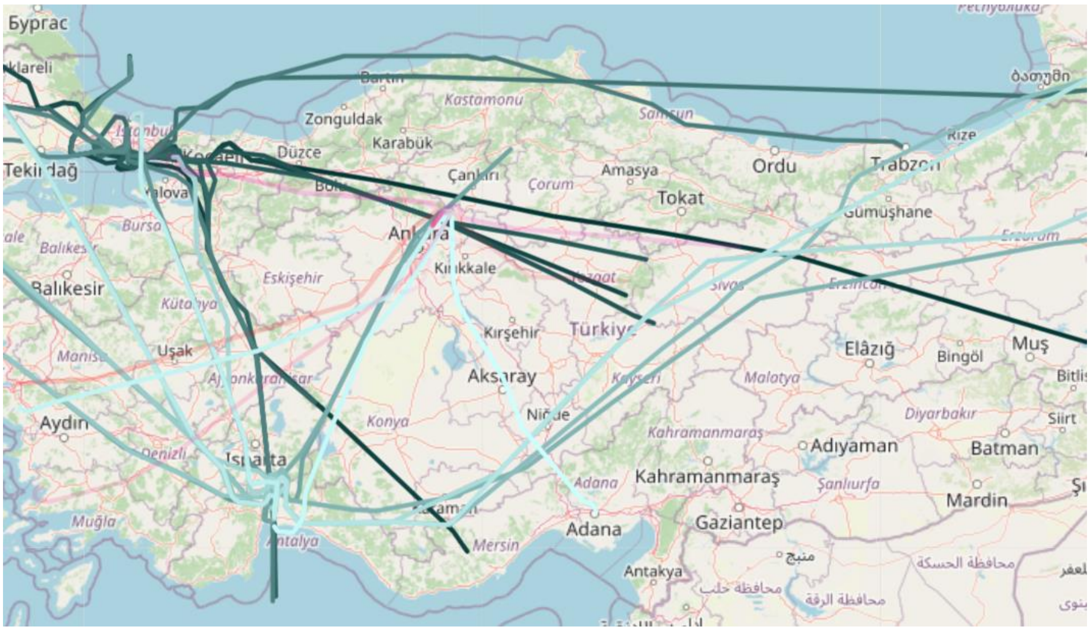

Figure 2: Aircraft flight trajectories.

After that, we compare the obtained set of airplane flights with the currently existing air route network of Turkey [19]. Due to the fact that when taking off and landing, airplanes performing instrument flights (and this is actually all commercial aviation) usually perform a standard instrument departure/arrival (SID/STAR). Also, we discarded this data to avoid distorting the final result Figure 3.

Since the collected data related to the flight of airplanes was with a frequency of 20-30s between the coordinates. The data was interpolated to have data with a frequency 1 s [20, 21]. We derived the equation of a straight line for the sections of the route, having the coordinates of the start and end points, using the sympy library, we get a point from which the height can be drawn to the selected straight line (we chose such points that one height was drawn to the beginning of the section of the route and the other to its end). As a result, we received another equation of a straight line corresponding to the height, so next we go through the flight coordinates until the equality is fulfilled, thereby determining when the plane flies in and leaves the selected area. After that, using the straight-line equation (1) we calculate the distance for each point (3). The obtained data are displayed in the histogram in Figure 4.

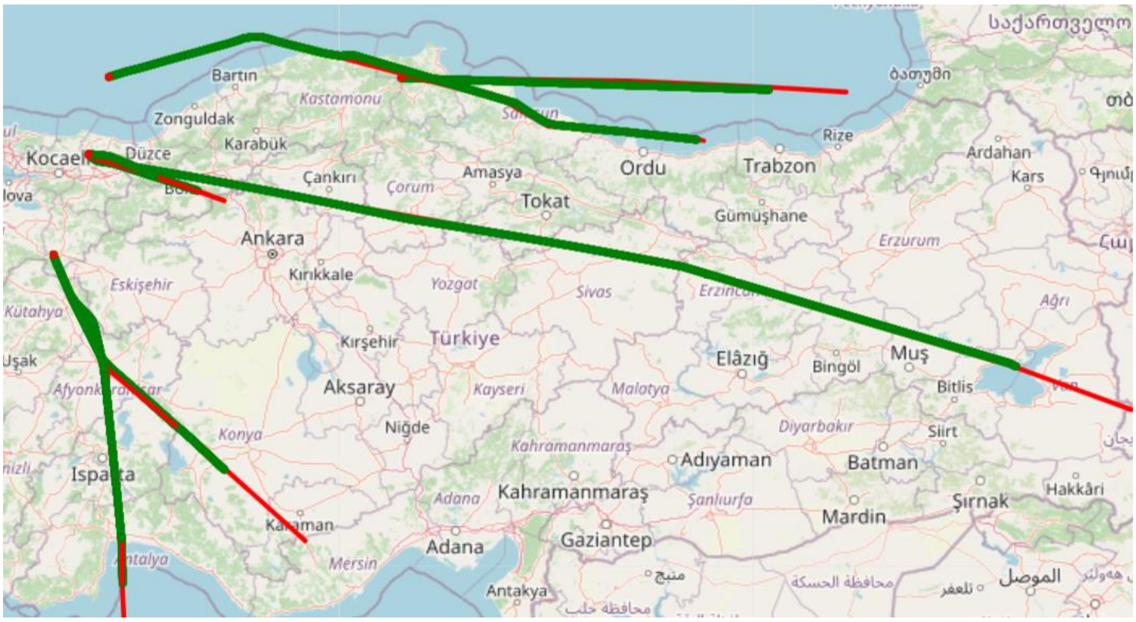

Figure 3: Superimposed flight curves on the routes along which they were supposed to fly.

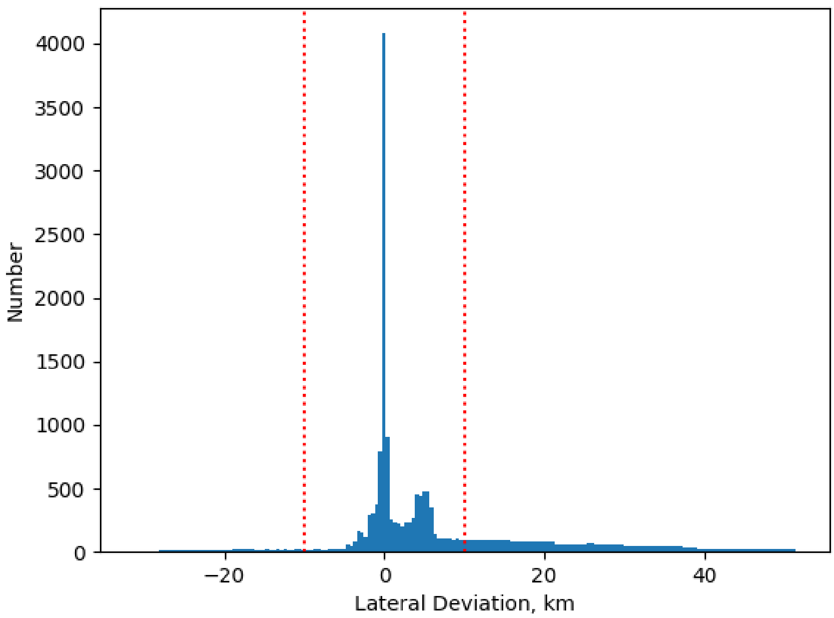

Figure 4: Histogram of the distribution of deviations.

As mentioned above, the lateral limits of the route can be different, but at the en-route stage, 10 km is usually used. Of course, the volume of the studied data is large, but they are discrete values, so we need to convert them into continuous values, for this we will use PDF (5). After processing the tuple of data regarding the deviation of the planes from the route, we got required parameters, the sampling mode μ = -1.17, the dispersion of the distribution σ = 10.12, the average value 7.17, k=0.5.

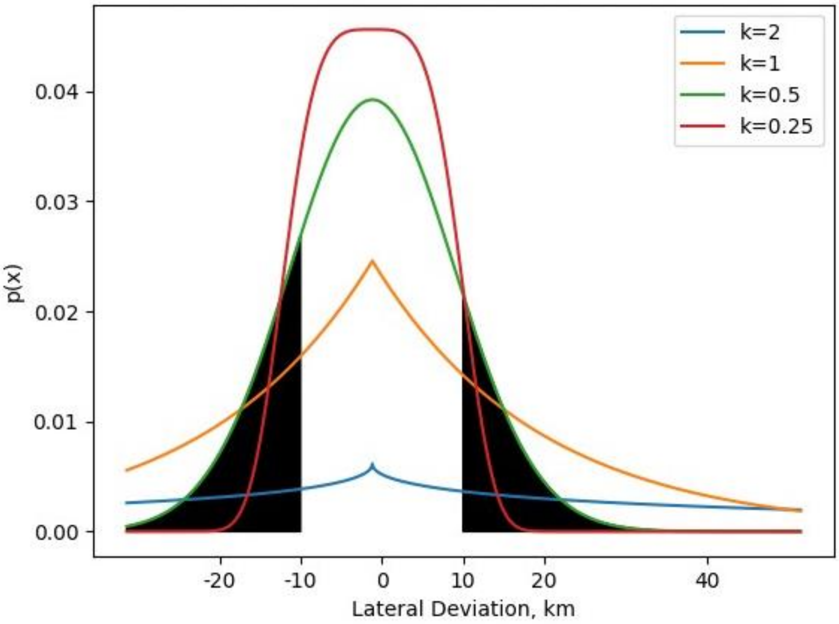

Figure 5: Estimated values of PDF.

Calculate the risk of the plane leaving the route by (4) (at Figure 5 this is indicated by the area with black color). The obtained value of R = 0.33 at k=0.5. For other values of *k* and the route, width are indicated in Table 1.

Table 1
The probability of the aircraft going beyond the route.

Specification	*K*=2	*K*=1	*K*=0.5	*K*=0.25
RNAV 10	0.55	0.01	1.11×10^{-16}	2.22×10^{-16}
RNAV 5	0.91	0.61	0.33	0.17
RNP 4	0.73	0.12	3.14×10^{-5}	2.22×10^{-16}
RNP 1	0.98	0.91	0.86	0.83

The obtained values show that the risk of an aircraft leaving the airspace of Turkey is quite high. However, this can be explained by the significant load on this airspace, because Turkey is a popular destination for many airlines, which leads to the fact that many planes can be in it at the same time. This leads to the fact that controllers resort to flow regulation and use echeloning as a tool to ensure a minimum of safety when performing a fly-by or overtaking aircraft on a route when applying speed regulation is not possible. For case of RNAV 10, the probability of going beyond the route is negligible, but this value is used for flights on routes over the ocean, which does not allow us to talk about its relevance for Turkey for objective reasons.

In the future, it will be possible to use the obtained data to calculate the total risk in the airspace of Turkey by (6). This will make it possible to understand whether the estimated value of TLS will exceed the established ICAO 5×10^{-9} or not. At the moment, it is only possible to compare the obtained results with similar studies where this value was calculated for other air spaces. For example, in the study of the probability of deviation for Ukraine [13], smaller values were obtained for all investigated values of route width, except for RNAV 10, it is smaller in Turkey.

5. Conclusions

During the study, data on the location of users in Turkish airspace relative to the routes they flew were collected and analyzed. The goal was to calculate the probability of deviation. An international network of ADS-B receivers located around the world, including one in Turkey, was used to obtain data on the location of airspace users. Statistical analysis of the accumulated data made it possible to estimate the deviation of users from the center of the route in the airspace of Turkey. Using a probability distribution function to fit the statistics. The estimated ND parameters made it possible to assess the risk of losing echelon in the lateral plane according to different navigation specifications. In the future, using the results of this study, it will be possible to calculate the risk of collision in the horizontal plane and the total risk for the airspace of Turkey as a whole according to the CRM Reich formula, in addition, it will be possible to determine the risk for the entire Black Sea region. The proposed method can also be integrated into the air traffic control system to assess the safety of the used airspace.

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