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Spatial modelling of midair collision risk using ADS-B data

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Abstract
The airspace environment is expected to continue increasing in complexity with the introduction of new types of air vehicles and operations and the projected growth of air traffic volumes. This creates a need for the development of new models to better understand the potential future states. This paper presents a geospatial model of a complex airspace environment which can be used to study any geospatially distributed entity within it. The methodology leverages Discrete Global Grid Systems (DGGS), a Geographic Information Systems framework previously utilized in the fields of geography and urban planning. The usefulness of the model is demonstrated on a case study that maps the geospatial evolution of the risk of midair collisions as a function of 3D location for four scenarios of increasing complexity in an airspace region of interest. The results from these four scenarios showed that the proposed methodology can be used to study the risk of midair collisions for different points in the airspace for any type of air vehicle and airspace region in a fully three-dimensional model that is capable of performing time varying analysis in a computationally efficient manner.

Keywords: geospatial model; airspace environment modelling; midair collision risk; air traffic data

Abbreviations: DGGS: Discrete Global Grid Systems, MAC: Midair Collision

1. A need for improved models of complex airspace environments

The airspace environment is a complex system. Its complexity can be attributed to many factors including its three-dimensional nature, the presence of diverse types of aircraft, the need for precise communication and navigation, weather-related challenges, airspace classes each with their own set of rules and regulation, international boundaries and considerations, and air traffic safety and capacity management challenges, to name a few [1, 2, 3]. Furthermore, the airspace environment is expected to continue to increase in complexity in the near future due to the integration of new types of air vehicles and operations [4, 5, 6] such as Urban Air Mobility (UAM) [7] and the forecasted exponential growth of air traffic volumes [5, 6]. [8] The National Academies of Sciences [4, 5, 6] explains that there is a need to investigate the development of new methods to model increasingly complex airspace environments.

The current paper presents a novel methodology for developing a geospatial model of complex airspace environments that is extensible to be used to study any geospatially distributed entity that is part of the environment. The model is required to satisfy the following:

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1. Air vehicle agnostic
2. Can be applied to any airspace region
3. Fully three-dimensional
4. Capable of time varying analysis
5. Computationally efficient
6. Scalable (area size, time interval, number of entities)

1.1 Overview of the airspace geospatial modelling literature

Geospatial models of the airspace environment have been used to study and improve the overall safety, efficiency, and environmental sustainability of the airspace system. For example, geospatial models have been used to improve airspace safety by analyzing terrain and obstacle obstructions near airports [9], for studying the impacts on the risk of integrating Uncrewed Aircraft Systems (UAS) in the airspace [10], or for modelling to mitigate weather-related incidents [11]. Starita et al. [12] also show how to make use of geospatial models predict congestion points in real-time for rerouting flights more efficiently. Wang et al. [13] also show how geospatial models can be used for planning airspace design concepts for Advanced Air Mobility operations. Lastly, geospatial models have been used for studying the environmental sustainability of the airspace system by Wunderli et al. [14].

Recent research focused on modelling complex airspace environments has made use of a new geospatial framework called Discrete Global Grid Systems (DGGS) [15, 16]. DGGS has been recognized as a foundation for the next generation of Geographic Information Systems (GIS) tools [17] because of its ability to integrate heterogeneous data types in a fully scalable and time varying three-dimensional representation. The Discrete Global Grid divides the Earth and the airspace above it into small cells or grids that are uniformly distributed [16]. DGGS have mainly found practical applications in the fields of geography, environmental studies and urban planning [18, 19]. Some examples of the use of DGSS in aviation research are its use in air traffic management to enhance the analysis and visualization of flight data [19]; for studying complex airspace environments for a use case identifying emergency airport sites [18]; and for in flight planning and navigation of uncrewed air vehicles [20].

2. Midair collision risk as a case study for modelling geospatial entities

The geospatial model of the airspace environment that is the subject of this paper will be implemented and demonstrated using a case study on midair collision (MAC) risk as the geospatial parameter of interest.

Midair collision risk models in aviation have evolved from early deterministic approaches, which relied on specific scenarios [21, 22, 23], to more complex probabilistic models like the Collision Risk Model (CRM) used by ICAO [24]. Modern techniques [25, 26, 27] employ Monte Carlo simulations for statistical outcomes, agent-based models [28, 29] to simulate individual aircraft behaviors, and Bayesian Networks [30, 31] to capture interdependencies in aviation operations. Furthermore, as aviation technologies such as Automatic Dependent Surveillance–Broadcast (ADS-B) become more prevalent, risk models are revised and refined to encompass model validation using real-world data.

To be applicable for the MAC risk case study that is the subject of this paper, the MAC risk model needs to meet the six requirements dictated by the complex nature of the airspace environment (see Section 1). Each of the reviewed MAC risk models were developed for a specific set of conditions, which enable them to be used effectively under these conditions but, to the best knowledge of the authors of this paper, none can simultaneously satisfy the six requirements above. To that end, a rudimentary MAC risk model is proposed and used for the case study presented in this paper.

3. The proposed geospatial airspace model

The modelling effort includes three main tasks : 1) collecting and processing air traffic data, 2) applying a DGGS framework to integrate the air traffic data in a structured geospatial model that includes uniformly distributed volumes and their centroids, and 3) calculating a geospatial, time-varying map of the risk of midair collision for each of the centroids at each time increment.

3.1 Data collection and processing

Historical ADS-B data was collected from the OpenSky Network [32]. The data represents the Thanksgiving weekend from November 23 to November 25, 2022 for two airspace regions: 1) a 5km^3 region centered on the LaGuardia (LGA) airport and 2) a 18km^3 region around the greater New York metropolitan area.

3.2 Description of the geospatial airspace model concept

A DGGS framework is used to integrate the air traffic data in a structured model that includes uniformly distributed volumes and their centroids.

3.3 The developed midair collision risk model

The proposed MAC risk model was developed to be simple in nature, using only the latitude, longitude, and altitude parameters from the collected ADS-B data, in order to maintain computational efficiency and scalability across different aircraft types, airspace areas, time intervals and number of geospatial entities under study. The risk model iterates over each centroid part of the DGGS grid and calculates the *relative position vectors* (shown in the figure) between these centroids and each ADS-B aircraft present in the airspace. This process is repeated for all time increments in the dataset. The *rates of change of each relative position vector* are calculated between each successive time increment and, using the relative position vectors and rates of change of relative position vectors, a *critical time* is calculated which corresponds to the hypothetical time each aircraft would take to arrive at the centroid location. For a midair collision to occur, both critical times of a pair of aircraft need to be near zero and must occur simultaneously. To that effect, the *risk metric* used in the developed model uses the smallest absolute difference of critical times between pairs of aircraft, where only those pairs of aircraft closest to the centroid are considered. The metric is calculated for all aircraft pairs with respect to each centroid as:

$$riskmetric = abs(ct_{(c1-a1)t1} - ct_{(c1-a2)t2}) + min(ct_{(c1-a1)t1}, ct_{(c1-a2)t2}) \tag{1}$$

Where $ct_{(c1-a1)t1}$ and $ct_{(c1-a2)t2}$ are the critical times at time t1 and t2 between centroids c1 and c2 and aircraft a1 and a2. The following results are presented using four different scenarios.

3.3.1 Single aircraft scenario

The first scenario is in the LGA airport terminal airspace for a single aircraft (N27WA) doing a flyby. Figure 1 shows the 3D risk map for all centroids for this scenario. The results show there is no risk of midair collisions (only one aircraft is present in the airspace for this scenario).

3.3.2 Two aircraft scenario

The second scenario is in the same airspace region at a different time and features an additional aircraft entering the airspace. In this scenario, the ASH6014 aircraft (in blue) is performing a landing on runway 31R at LGA while the aircraft N27WA (in orange) continues doing a flyby over the region. Figure 2 shows the evolution of the 3D risk map for all centroids for this scenario at 4 different times.

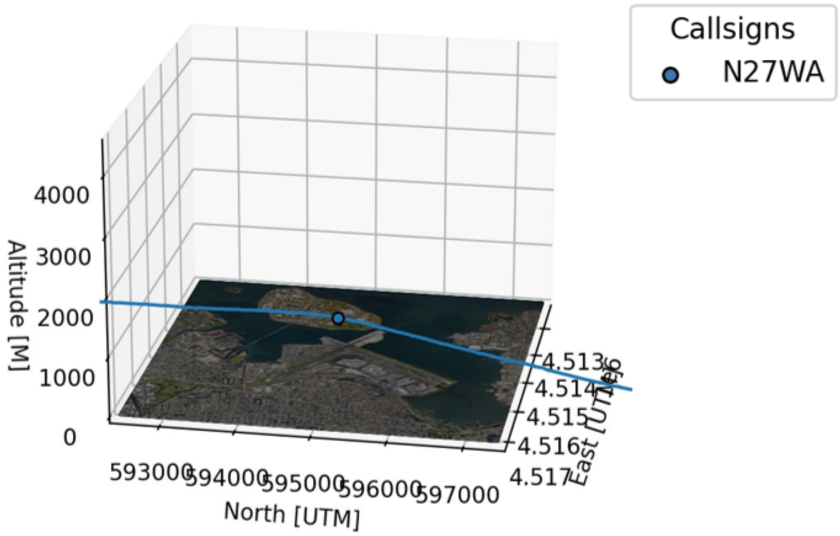

Figure 1. Single aircraft scenario

The most severe risk values correspond to lower values of the risk metric (red regions). Centroid locations resulting in no chance of any collisions occurring are colored transparent in the figure. The results show that as the aircraft get closer to each other, the size of the area resulting in possible midair collisions becomes progressively smaller from Figure 2a to Figure 2d. In addition, as the aircraft get closer to one another, the worst value of the risk metric becomes more severe (more red). Finally, the risk map of the last time shown in Figure 2d shows that as the ASH6014 aircraft nears the end of its landing the size of the area resulting in possible midair collisions (all colored centroids) shrinks down to almost nothing.

3.3.3 Three aircraft scenario

The third scenario is in the same airspace region as the first two, but uses a different time interval and features three aircraft. Figures 3a through 3d depict 4 times for this scenario. In this scenario, the RPA4772 aircraft (in orange) is performing a landing on runway 31R at LGA, the aircraft RPA4512 (in green) is executing a takeoff on runway 4L at LGA, and the aircraft N27WA (in blue) is doing a flyby over the region. These results show that the geospatial model can be scaled to work for more than 2 aircraft, showing the geospatial distribution of risk that combines the risk of more than two aircraft. This scenario also illustrates a challenge encountered in this research with respect to trajectory smoothing.

3.3.4 Multiple aircraft scenario

The fourth scenario makes use of the second ADS-B dataset. This scenario shows results involving more than 3 aircraft (12 aircraft are shown in this example). Figures 4a through 4d depict 4 times for this scenario. It is important to highlight that because the model is *combining* the risk of midair collisions between all possible pairs of aircraft for each centroid, the results become increasingly difficult to interpret as the problem space becomes more complex. The results shown in Figure 4 demonstrate this observation and shows that there is a need for methodologies to interpret more complex airspace environments. One such example that could be used to address this challenge is the use of machine learning tools [33].

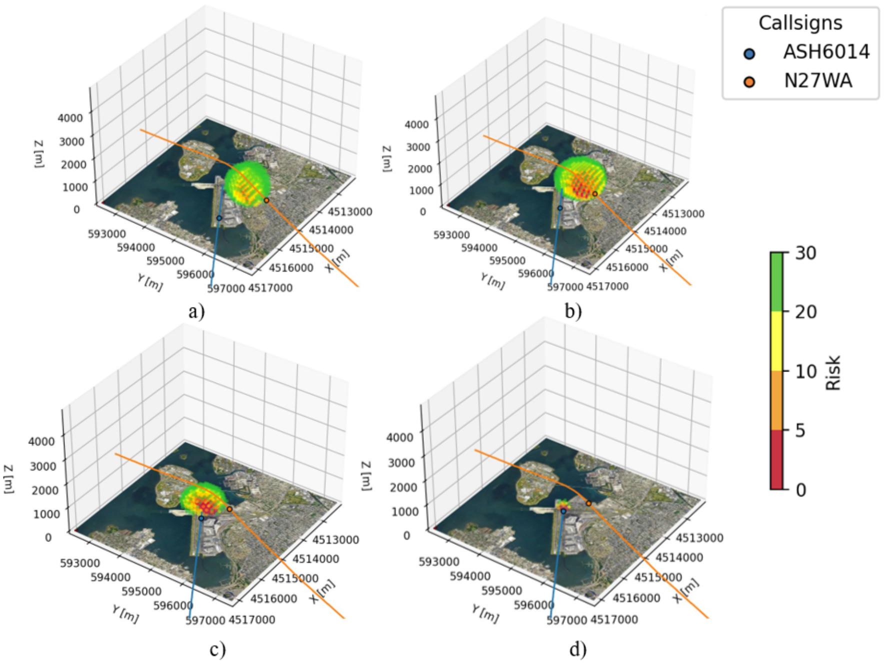

Figure 2. Two aircraft scenario

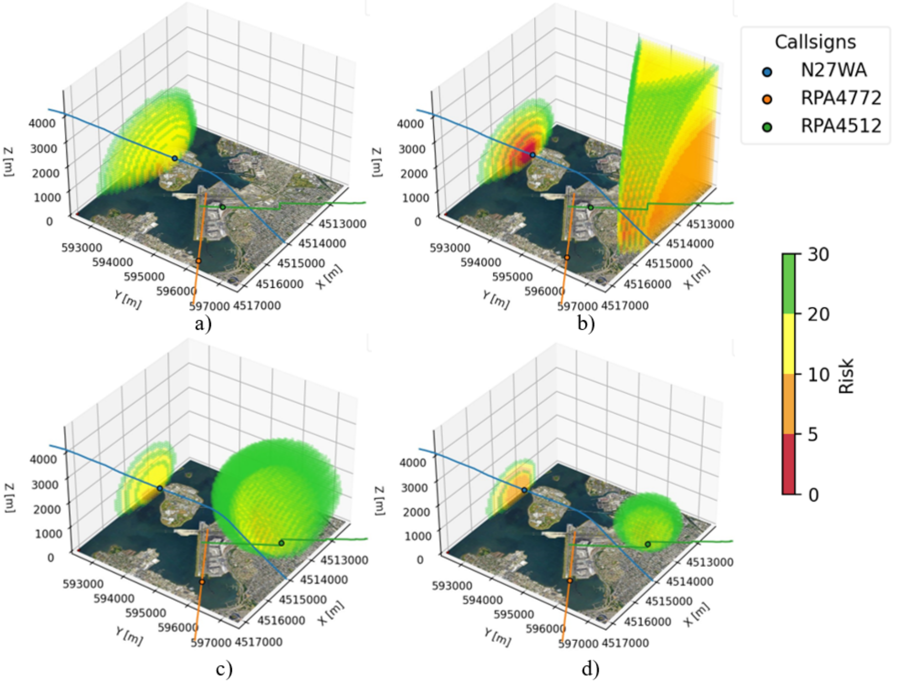

Figure 3. Three aircraft scenario

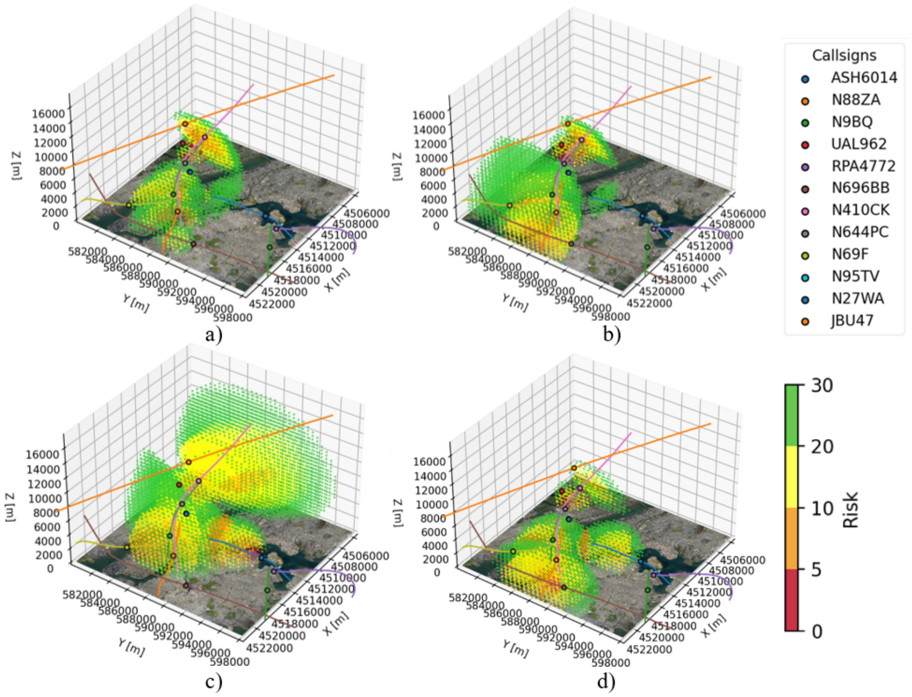

Figure 4. Multiple aircraft scenario

Author contributions

- Nicolas Vincent-Boulay: Conceptualization, Data Curation, Methodology, Software, Formal Analysis, Writing - Original draft, Visualization
- Catharine Marsden: Supervision, Formal Analysis, Writing – Review and Editing

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Open data statement

All datasets used in this research are pubicly available ADS-B datasets that can be accessed using the Python API [32]

Reproducibility statement

For all aircraft pairs and centroids of the DGGS grid, the risk metric equation (equatin 1) can be used to reproduce all results obtained that were presented in the paper.

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