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Probabilistic risk assessment: Hazard impact study of safety-critical space launch events onto world air traffic & creation of ADIONA software

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ABSTRACT

Space and air traffic increase yearly, prompting concerns about their coexistence. Fallback and splashdown of rocket stages to earth into predefined areas is a usual scenario, explosions of rockets and fallback into unprecedented areas is a probable scenario. These events represent a threat to world air traffic. In the present study, a probabilistic risk assessment on the launcher's stages fallback onto world air traffic has been carried out. A novel method and software, ADIONA, were developed to assess risks of rocket explosions and debris impact on air traffic. This pioneering software, a venture of the Flight Safety Department of the French Space Agency (CNES), supervising European Space Agency (ESA) launches, calculates at every possible time instant, defined by the user, the estimated positions of airplanes with along their own trajectories, trajectories and positions of rockets and the corresponding areas where debris falls back on earth after an explosion or a deviation. It further assesses the risks of fall down of debris on air traffic in case of a launch mishap and the probability of fatality to an airplane regarding the risk boundaries set by the French Space Operations Act. The software has been implemented in a general way for broad future application in operations and continued studies and use. Real-world air traffic and rocket launch data were incorporated, particularly focusing on launches from the French Guiana Space Center (CSG) and air traffic over the North Atlantic Ocean. These real-world analyses represent realistic scenarios. The obtained results show a considerable high possible risk onto world air traffic in case of a rocket explosion after launch. It is concluded that the cohabitation of space and air traffic and the probabilistic risk assessment thereof is important to be monitored in order to eventually be diminished to reduce the risk. It is recommended to invest further resources into this observation type of analysis. Further investigations should take place on this probabilistic risk analysis, taking into account more details and fine-tuning in the risk calculation and assessment method. The study's findings and software lay the groundwork for future risk analysis and development, facilitating ongoing and future investigations.

1. Introduction

Increasingly crowded airspace due to both space-bound systems and aviation traffic poses challenges as aviation relies more on space-based safety-critical services. Rocket launches traverse multiple airspaces, posing risks to densely occupied airspace. Commercial spaceports are growing, necessitating ad-hoc safety regulations for air launches. To mitigate risks and ensure safer space travel, proper assessment, monitoring, and reduction of risks are imperative.

The Flight Safety Department at the French Guiana Space Center (CSG) is responsible for safeguarding people, goods, and the environment throughout all phases of a rocket's flight, including launch preparation, decommissioning, and potential abnormal events. Hazard areas associated with launches are declared beforehand, prompting measures like issuing Notices to Airmen (NOTAMs) to alert pilots. With increasing space and air traffic, the risk to air traffic and population intensifies without adequate prediction and monitoring.

Abbreviations: CNES, Centre National d'Etudes Spatiales (French Space Agency); CSG, French Guiana Space Center; NATs, North Atlantic Tracks; NOTAM, Notice to Airmen; RFL, requested flight level.

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Previous studies suggest a low probability of debris striking commercial aircraft but highlight potential casualties without pilot intervention. A new probabilistic risk assessment using the ADIONA software analyzes the risks of rocket explosions and debris impact on air traffic using real-world data from the French Guiana Space Center for rocket trajectories, and real-world data from EUROCONTROL for airplane trajectories. This study marks the initiation of a new investigation sector within the Flight Safety Department of CNES, overseeing ESA launches.

1.1. Literature review

This section presents the state-of-the-art in current literature. The literature focuses mostly on deriving the debris field contours, looking at details of how debris can impact an aircraft, or the way to optimize aircraft around an exclusion zone.

Modelling risk of debris to aviation requires consideration of the probability of launch failure, debris size [1], debris propagation and distribution [2,3], debris envelopes or risk contours [4–6], aircraft positions, re-routing and effects on aircraft [6–12], debris impact with aircraft and probability of casualties [2,13–20], target levels of safety [4,21,14,22], and, software development and simulation [6,15,23]. Fuentes et al., in 2015, [6] present an initial risk assessment for aircraft by France, using a grid-based density estimate of aircraft positions; although this initial work does not include debris fields or launch trajectories.

There have been numerous studies related to rocket reentry and the risk to aviation.

Tinoco et al. [8] emphasize that with increasing space launch cadence and airspace closures, conflicts between commercial space and aviation entities are on the rise. This paper addresses the gap in research on integrating commercial space operations into the National Airspace System (NAS), particularly concerning impacts on international carriers and general aviation (GA). By exploring the potential impacts of launch and reentry activities on aviation, it focuses on identifying affected flights and assessing airspace closures using simulation techniques.

Tinoco et al. [9] give a good review of the literature associated with this area including [8,13,20,22,24–28]. The paper [9] estimates economic and operational impacts of commercial space horizontal launches on airlines using fast-time simulation modeling, focusing on Cecil Air and Space Port in Jacksonville, Florida, and NAS rules. Results show that the existing 4-hour airspace closure rule significantly affects flights, causing delays and additional costs. Safely reducing airspace closure duration could mitigate these impacts. Additionally, treating studied launch vehicles as aircraft and opening departure/arrival corridors during launches could substantially alleviate airline impacts. This study also highlights important policy implications for safe and efficient integration of space activities into airspace, emphasizing the need for fair and equitable solutions. While some of these studies [6,13], illustrate quite sophisticated tools, the difficulty is having these methods usable by other space and aviation authorities.

The three papers by Firdu Bati et al. [4,21,29] summarize the risk assessments involving space debris and aircraft, although the debris field is modelled as contours of risk, rather than a single outer envelope. The goal of these papers was to define the appropriate exclusion zone for aircraft, which depends on an acceptable level of risk and as such, limits of the exposure time of aircraft in each risk contour.

As described in [30], a fragment from a reentering space debris impacts a commercial aircraft, destroying the plane and killing all passengers and crew is described as a Black Swan event, a rare event with severe consequence that is historically unprecedented and deemed too unlikely to demand mitigation. In [30], this event is viewed not only as foreseeable but an obvious eventual outcome.

W. Ailor [31] predicts for 2030 that the probability of debris from reentries of satellites of large constellations striking a commercial aircraft would be 0.001/year, and without emergency action by pilots, the maximum yearly casualty expectation for reentries of satellites disposed from a single large constellation for people in aircraft could be 0.3/year. According to the paper, those estimates would be higher if commercial air traffic were updated to include all worldwide flights.

The FAA in 2021 [18], in a report to Congress, notes "Debris fragments of 300 gs or larger are conservatively assumed to be able to cause at least one serious injury or worse to an aircraft occupant and could lead to an uncontrolled aircraft landing with catastrophic loss of life to many or all people on board." The paper notes that a 9-gram steel mass is sufficient to penetrate an aircraft. The FAA report uses a 300 people on board estimate as 'conservative'. The aircraft vulnerability area used as 1000 m^2. This paper gives calculations for the effective risk area based on descent speed and aircraft speed.

Bellucci et al. [5] quantify the aircraft vulnerability area at 1150 m^2, based on a, in the paper, derived average aircraft in terms of dimensions and proportions with a characteristic airplane length defined as 65,18 m, as well as the proportions of an Airbus A350.

Bellucci et al. [5] further consider that a space debris larger than a square of 10 cm x 10 cm carries sufficient energy to perforate the structure of the aircraft. This threshold of 100 cm^2 is chosen to estimate the consequences on aircraft of an eventual impact with a space debris. Furthermore, [5] states that CNES studies have shown that debris smaller than this size are ablated during reentry.

Colvin and Alonso, 2015 [7], describe a tool for 4-dimensional definitions of exclusion zones for a launch (horizontal, vertical and time) with their SU-FARM module available in Python as open-source software via git-hub (Colvin 2016 [32]). SU-FARM probabilistically analyzes the risks posed by launch and reentry events to aircraft operating in the NAS (National Airspace System).

Capristan and Alonso, 2014 [3], looking at the risk to people on the ground, quote the accepted risk by the FAA for licensing in terms of casualties per mission of 3×10^{-5}. The paper demonstrates models for debris propagation and resulting contours of debris. An open-source analysis environment called Range Safety Assessment Tool (RSAT) has been developed to assess ground risks, including inert and explosive debris effects, debris toxic gas dispersion, and blast overpressure. RSAT utilizes random sampling techniques to calculate safety metrics like expected casualties per mission (ETC) and features a trajectory optimization tool for establishing nominal trajectories. The paper demonstrates RSAT's application in analyzing launch and reentry accident scenarios.

The French Space Operation act [24] defines the accepted risk in terms of casualties per mission of 2×10^{-5}.

2. The software – ADIONA

2.1. ADIONA

In this chapter the software's development is described which has been named ADIONA. The name has been chosen because in Roman mythology Adiona was the goddess of the return journey. According to the stories, she protects travelers on their way home. It was decided on this name because it suits very well as the software will protect air passengers from danger during their travel.

ADIONA calculates the estimated trajectories of planes and their estimated positions, the trajectories of rocket launchers and their positions, and calculates the probability of impact on the planes in case of an explosion during the launch. In the following sections the specifics of ADIONA are described.

2.2. Creation in python

Python was used as the programming language. Due to the high desire to visualize the results on a world map, Folium with GeoPandas has been used. Its straightforward applicability and the fact that the combination of Python, Folium and GeoPandas is already used in other big industries, for instance in the maritime logistics industry, have been deciding factors for this decision.

2.2.1. Folium with geopandas

Folium allows the visualization of results on a global map in an interactive way; it is an interactive mapping tool. The advantages are that results are displayed on a global map and one can easily zoom in to every detail. Using special commands in Python one can access and open the Folium tools. GeoPandas is an open-source project that simplifies working with geospatial data in Python. GeoPandas enables to easily do operations in Python without requiring special databases. Python, Folium and GeoPandas go hand in hand.

2.3. Sequence in ADIONA for airplane flights

2.3.1. Input data

As input data, ADIONA takes a database of flights in the form of an Excel sheet. The input data consists of arrival and destination airports (names and coordinates), flight level and flying distance. The flight level is an aircraft's altitude at standard air pressure, expressed in hundreds of feet. Because these were the only given data available at the beginning of the study, the software has been set up using only these input data.

2.3.2. Calculation of flight time

In a first step, a function is implemented which transfers a time format of HH:MM:SS into seconds and into minutes as this format will be used in the following steps in the software. What follows is a calculation of flight time as the difference between time of arrival and time of departure.

2.3.3. Geodesic line

Since the only input data were arrival and destination airports, namely their names and coordinates, flight level and flying distance, the actual flight path and its coordinates of every instant during the flight were not given. Hence, a solution needed to be found to approximate the flight paths as precisely as possible, to then, in a later step, extract the location of airplanes at different time instants which are inputted by the user.

A geodesic line is the line on Earth's globe with the shortest distance between two points. It was decided to start off with a geodesic line and implement it between the departure and arrival airports. An error calculation served as a verification for this procedure, as explained in a next section.

2.3.4. Dynamically adjustable length

The geodesic line is created in a way that it depends on an input number which is the number of parts the line consists of. For instance, if this input number is 10, the geodesic line will be calculated and displayed as an ensemble of ten different lines of equal distance that are connected and lead from the departure airport to the destination airport. It is desired to make this input number as small as possible but not smaller as necessary, as this increases calculation run times.

This input number is hence defined as the division of the flight length by the length that the airplane advances per minute. In this way, when running the software for different flights simultaneously, it is made sure that all these pieces that compose the geodesic line provide the same length, which is adjusted to be the interval of one minute. Hence, in the following steps, estimated airplane positions can be defined by the accuracy of one minute. Would one need to change this accuracy, one would only need to change this division number and trim it to another specification. Therefore, this number is referred to as dynamically adjustable.

2.3.5. Error calculation

As a next step, an error calculation was done to verify that the chosen methodology is acceptably accurate. As mentioned previously, one of the input data was the effective flight length. As an additional parameter, the length of the geodesic line was calculated and thereafter compared to the effective flight lenght in the error calculation. Depending on these results it was decided whether the chosen approach will be developed further.

The error calculation has been carried out for the input data which is described in the next chapter. This input data covers the range of one month. Hence, to validate the established method, it has been applied on every day of this one month. The results and average deviation of the effective flight length and the calculated flight length have been calculated with a geodesic line for every flight over this one month.

The results showed an average error of 2.99 percent. As the input data is extremely limited it was decided that this error is acceptably small. This study started from scratch and hence to obtain the first results to see in which range the risks on airplanes are, this error is considered small enough. It is noted that due to the lack of more given input information a geodesic line calculation is used; flight corrections, e.g. due to weather, are therefore not included.

2.3.6. Accessing estimated airplane position at specific time instant

As in the case of a possible rocket explosion it is of interest to know the estimated position of all the aircraft at a given time over the Atlantic at this specific time instant, it is necessary to be able to access the estimated position of every airplane at a desired instant in time.

The software subsequently calculates the time and estimated position via the previously defined step division of the geodesic line. As a result, one can access every interval on the flight trajectory, and the software calculates different parameters at each of these time intervals. Examples of such calculated parameters are for instance: currently flown flight length (in nautical miles and kilometers), current time, and time spent in the air since departure. Using direct accessibility of these timesteps is also how the determination and visualization on the map of the current estimated airplane position works.

A time instant can be inputted by the user of the software. The software will then run through every segment of every flight trajectory and stop at the inputted time instant. For instance, the user inputs a specific day and time, and the software runs all the calculations until the specific day and time are found represented in the results that lay on the intervals. At this point, the calculation stops, and the desired estimated positions of all airplanes are found.

Now, in a next step, these estimated positions as well as the flight trajectories are outputted and can be visualized on the map, such as in Fig. 2, Fig. 3 and Fig. 4. All blue dots present the airplanes' estimated positions at the same instant in time.

2.4. Sequence in ADIONA for rocket launches

2.4.1. Launch trajectories

As an input data for the launch trajectories CNES' internal files have been used. They have been transformed into Excel files which are thereafter read into Python. Once imported into ADIONA, the desired launch can be chosen for calculation. The launch trajectory is displayed on the map as well as the current position of the launcher. Again, the software is developed in a way that one later can choose the exact time instant of interest to calculate and display.

2.4.2. Taches (Hazard areas)

The principal for the depiction of hazard areas, subsequently referred to as the French word "taches", is similar to the launch trajectories. A file created by CNES' accidental explosion simulation software is transferred to an Excel file and read into ADIONA. Again, the software is developed in a way that one later can choose the exact time instant of interest to calculate and display. An explanation of taches is given in Section 3.3.

2.4.3. NOTAM zones

The NOTAM zones concerning the launcher's stages fallback are defined according to the CNES documents, read into ADIONA, and displayed on the map. Fig. 5 depicts flight trajectory with taches and NOTAM zones.

2.4.4. Probability calculation

The probability calculation has been carried out after extracting the data and results about estimated airplane positions and taches locations from ADIONA.

3. Methodology

This chapter describes the methodology and the applied approach, as well as how the given input data are inputted into ADIONA which lead to the results.

From the French Guiana Space Center in Kourou most rockets launch towards the north, crossing the eastern or western part of the North Atlantic Ocean. The rocket stages' drop zones are located mainly in the North Atlantic Ocean. Therefore, they cross the North Atlantic Tracks (NATs). The North Atlantic Tracks is a structured set of transatlantic flight routes that stretch across the Atlantic Ocean from eastern North America to Western Europe. These heavily travelled routes are used by aircraft flying between North America and Europe. Rockets launching to the east from French Guiana do not interfere with major air traffic, while the last stage's drop zone is located west of the African continent.

Therefore, this study focuses on the cohabitation of air traffic over the North Atlantic Ocean and rocket launches from the Guiana Space Center heading north.

3.1. Preparation

3.1.1. Data from EUROCONTROL

Real-world data on air traffic on the North Atlantic Tracks (NATs) provided by EUROCONTROL serve as input data to ADIONA's airplane flights sequence. The given data consists of real information about 34′000 flights, over a period of one month, which took place from 16/07/2021 - 12/08/2021. The data contains: Date of Flight, Airspace Type, Stat Name, Flight ID, Call Sign, Origin ICAO Airport Name, Destination ICAO Airport Name, Off Block time, Take Off Date, Take Off Time, Arrival Time, RFL (requested flight level), Airline, Aircraft, Wake Vortex Category. It is noted that the time format was given by EUROCONTROL in European format for the European Space Port in French Guiana, which is day/month/year, hence this format is subsequently used in this paper.

The exact coordinates of departure and arrival airports have been missing. Hence, the supplement of 34′000 coordinates of departure and 34′000 coordinates of arrival airports has been done using a separate database. This completion was necessary because the calculation in ADIONA requires the precise coordinates of every departure and destination airport.

3.2. First analysis of flight distribution

The flight distribution has been analyzed to obtain the time windows with the highest and lowest density of airplanes and run the later performed simulations in ADIONA of airplanes and rocket launches in these exact time frames. This approach allows to set the circumstances for the full spectrum of results: highest probability of impact and lowest probability of impact with regards to outer circumstances in case of a launch trajectory deviation and launcher stage's fallback outside of the NOTAM zone or a launcher's-controlled explosion.

3.2.1. Histogram of number of flights per day

Fig. 1 depicts a histogram of the flight distribution over the given data set.

The highest number of flights per day took place on 09/08/2021 with a total number of 1346 flights. The lowest number of flights per day took place on 21/07/2021 with a total number of 1118 flights. The average of flights per day over the entire time span from 16/07/2021 until 12/08/2021 amounts to 1238 flights per day.

In a next step, it has been investigated during which time of the day the density of airplanes over the North Atlantic is the lowest for 21/07/2021 and the highest for 09/08/2021 to obtain the time windows of interest to this study.

3.2.2. 21/07/2021: day with least flights per day

As per the given data, namely the UTC times of departure and arrival, it is not possible to directly extract the time at which the airplanes are at a certain position on their trajectory, i.e. at a specific coordinate over the North Atlantic. It has hence been decided to analyze in a first step the distribution of times of departure over the entire day.

The time of departure does not correspond to the instant in time over the North Atlantic. As all the given data are flights departing on the east and west coast of the North Atlantic, an approximation is made that it takes them between one to five hours to reach the area of the North Atlantic after departure. Hence, the number of planes over the North Atlantic corresponds to the number of planes having departed one to five hours before the instant in time of interest. It should be noted that there will be exceptions and deviations of this assumption, especially for flights departing from the Far East, from North America's west coast or South America. However, after careful consideration, plotting of many flight trajectories, and analyzing that these flight trajectories lead more north or south and outside of the high-density airplane routes over the North Atlantic, which are of interest to this study, it was decided that the vast majority of flights in the area of interest for this study fulfills the assumption made.

Therefore, the instant in time when the lowest number of planes are to be assumed over the North Atlantic corresponds to the instant in time before which the sum, respectively the integral, of departed planes during one to five hours before the time instant of interest is the lowest.

The analysis showed that the time of 21:00 UTC corresponds to the lowest density of planes over the North Atlantic on 21/07/2021, which is the day with the lowest flight density within the given data set from 16/07/2021 to 12/08/2021. This therefore corresponds to a local minimum. To examine the time span with the absolute lowest density of flights over the North Atlantic, the global minima, during the entire period of given data a deeper analysis would be needed. However, it was decided that this procedure as a first approach meets the needs of this study.

3.2.3. 09/08/2021: day with most flights per day

Therefore, in the example of 09/08/2021, the instant in time at which the highest number of planes are to be assumed over the

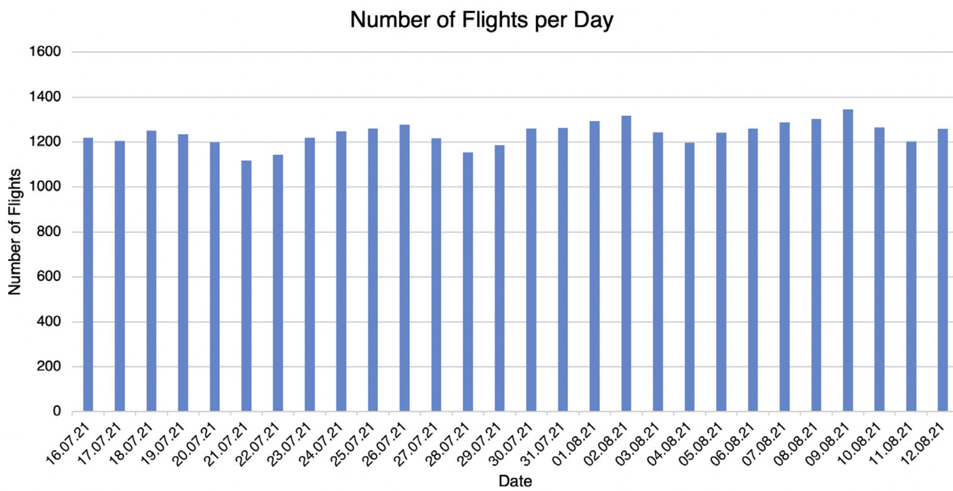

Fig. 1. Histogram of number of flights per day over one month.

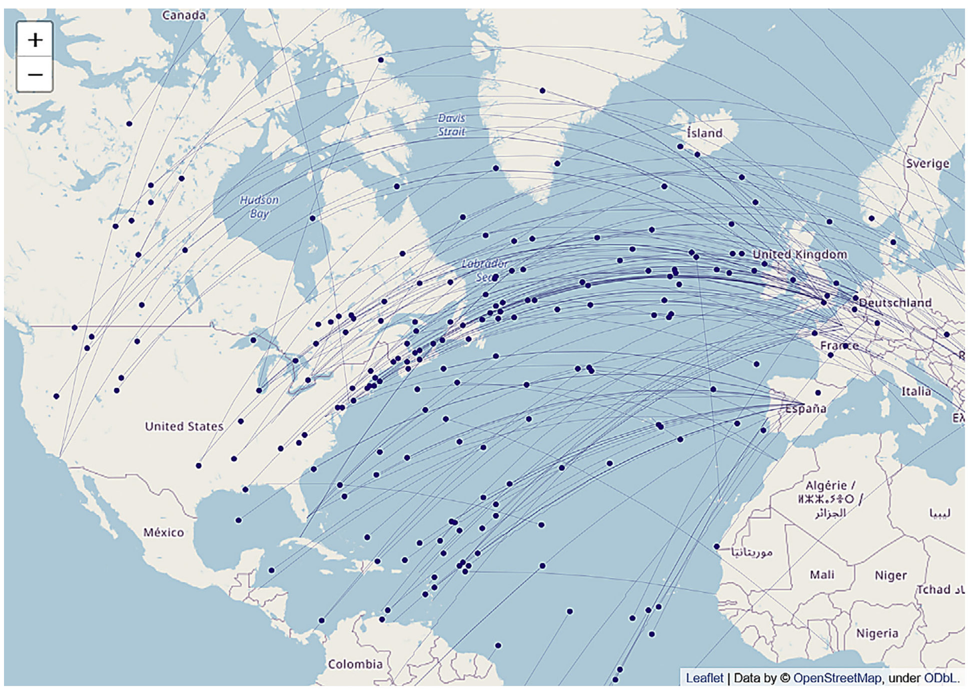

Fig. 2. Flight trajectories and airplanes, visualized on 21/07/2021, at 21:00 UTC.

North Atlantic corresponds to the instant in time before which the sum, respectively the integral, of departed planes during one to five hours before the time instant of interest is the highest.

The analysis showed that the time of 13:00 UTC corresponds to the highest density of planes over the North Atlantic on 09/08/2021, which is the day with the highest flight density within the given data set from 16/07/2021 to 12/08/2021. This therefore corresponds to a local maximum. To examine the time span with the absolute highest density of flights over the North Atlantic, hence the global maximum, during the entire period of given data a deeper analysis would be needed. However, it was decided that this procedure as a first approach meets the needs of this study.

3.2.4. Flight trajectories visualized at two instants in time

Fig. 2 depicts the situation on 21/07/2021 at 21:00 UTC, the instant in time derived to have the least airplanes over the North Atlantic Ocean.

Fig. 3 depicts the situation on 09/08/2021 at 13:00 UTC, the instant in time derived to have the most airplanes over the North Atlantic Ocean.

After analyzing Fig. 3 it was concluded that the western part of the North Atlantic, namely the Labrador Sea, is not as densely covered by planes as the eastern part of the North Atlantic. It was hence decided to investigate the situation two hours later (15:00 UTC) as well. The situation at 15:00 UTC is depicted in Fig. 4.

Because of the denser airplane distribution at 15:00 UTC than at 13:00 UTC over the North Atlantic Ocean's western part, it was decided to move forward using both time instants: the one of 13:00 UTC for rocket launches towards the northeast of the Atlantic and the one at 15:00 UTC for rocket launches towards the northwest of the Atlantic.

This chapter investigated the different deciding boundary parameters for the study at hand. The day of minimal number of airplanes as well as maximal number of airplanes has been in-

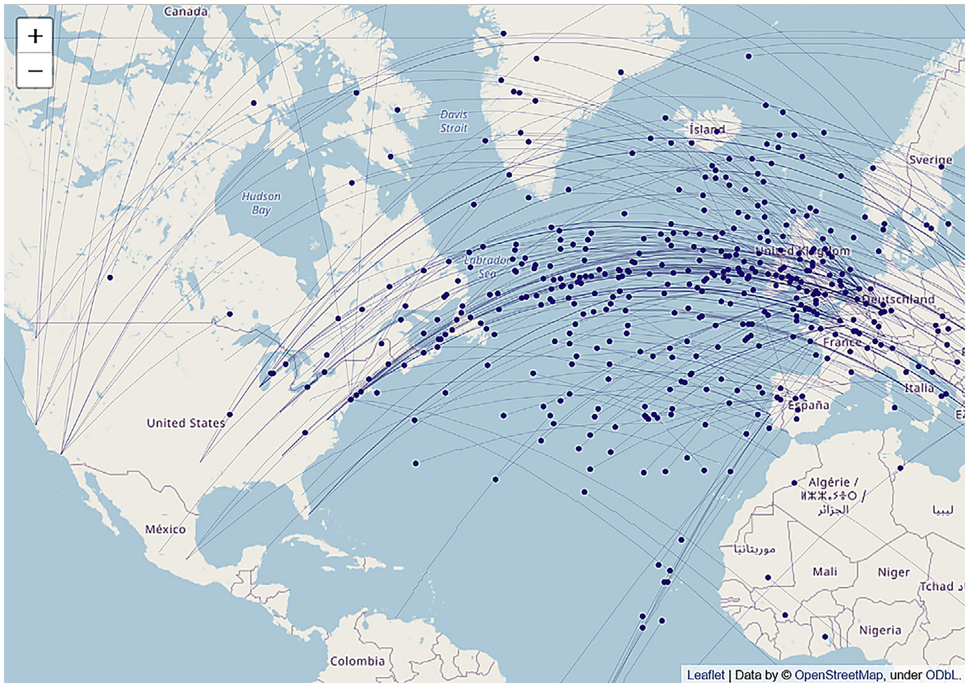

Fig. 3. Flight trajectories and airplanes, visualized on 09/08/2021, at 13:00 UTC .

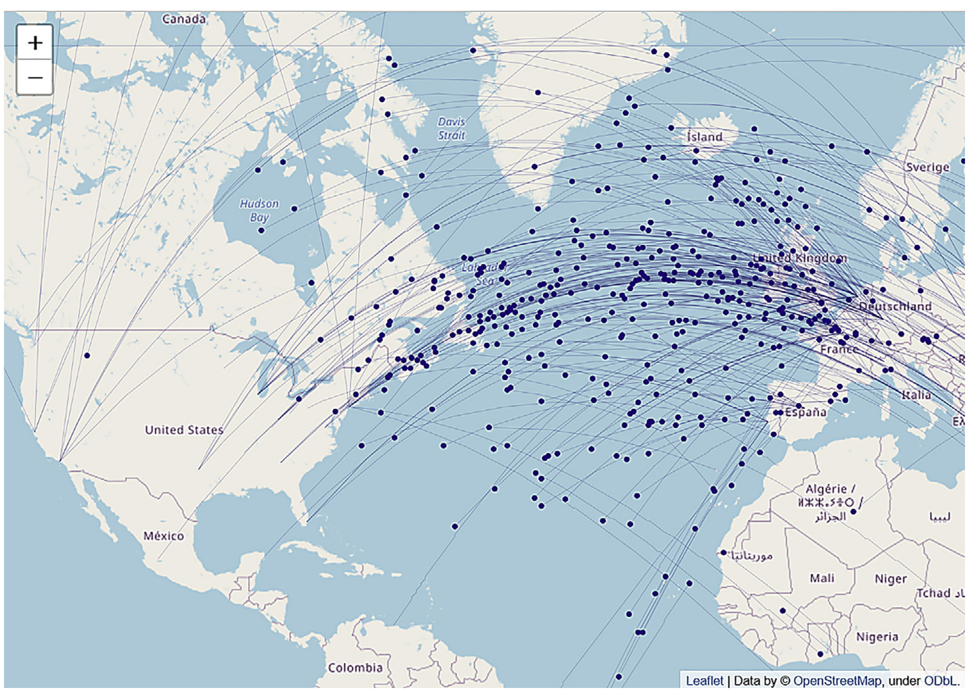

Fig. 4. Flight trajectories and airplanes, visualized on 09/08/2021, at 15:00 UTC .

vestigated over the period of given data from 16/07/2021 until 12/08/2021. Furthermore, during these two days, the time instant of minimal and maximal number of airplanes over the North Atlantic was determined.

Both time spans, the one representing the lowest plane density as well as the highest plane density over the North Atlantic, can be implemented in the primary simulations and analyses of launch trajectories in ADIONA. This paper later focuses on the results of the upper limit, i.e. the highest plane density.

3.3. Area at risk around an airplane

3.3.1. Flight level

The majority of aircraft in the NAT are within the expected flight level range of 350 to 410 with mean 380. This value corresponds to an absolute height of 11.58 km above sea level and should hence be considered for the further investigation in the study. The surface of impact in this study is not the ground level, but the flight level where all the airplanes are located.

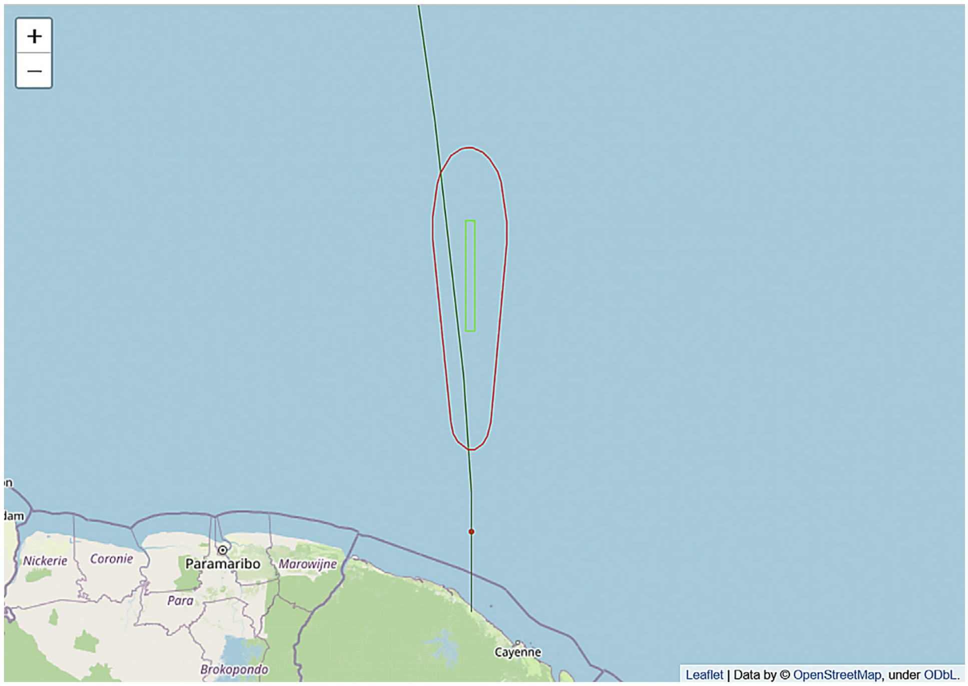

Fig. 5. Tache of Sample 1, 120 s after lift-off. The red contour line (the tache) represents the expected boundary of debris due to a launcher's explosion at the given time. The dark green line represents the rocket path, the red dot is the rocket's position at explosion, the light green rectangle is the NOTAM exclusion zone.

3.3.2. Taches

Every tache is a set of a precisely calculated number of coordinates creating an envelope around all the debris that is calculated to fall down on earth after a launcher's explosion at this specific time instant. With CNES' accidental explosion simulation software, the specifics of every tache at different time instants after launch can be generated.

There are two reasons an explosion of the launcher could take place: i) The Flight Safety unit would detect anomalies in the rocket's behavior and define the launcher as dangerous. In this case, the launcher would be destroyed to meet the safety requirements set by the French Space Operations Act [24]. This time span of interference by the Flight Safety unit can take place until a predefined time after launch. ii) The launcher would behave nominally; the Flight Safety unit would not interfere, but other technical problems would lead to an explosion. In both cases all the debris would fall within the tache at the specific time instant of the explosion.

Fig. 5 depicts an example where the tache of a launch from the Guiana Space Center is illustrated in red after lift-off. Also illustrated is this launch's flight trajectory in the color dark green as well as the position of the launcher in this specific time instant as a red dot. The light green rectangle is one of the NOTAM zones. The image has been generated by using ADIONA.

One can well observe that the launcher is still very close to the launch site at CSG but the debris would already be propelled significantly further along the launcher's trajectory in case of an explosion.

The use of taches in this study would not apply at sea level but at flight level where all the airplanes are located. The specifics of taches cannot be extracted by CNES' accidental explosion simulation software at another level than at sea level because of its development. Currently, taches cannot be extracted at flight level. Thus, in this study, it was necessary to consider the taches at sea level which, by the laws of physics of the debris falling on the ground, are larger than the taches at flight level affecting the aircraft.

4. Results

The constructed software ADIONA has been applied to different launches that have been launched in the past from the Guiana Space Center and different sequences thereof have been analyzed. After obtaining these first real-world results with ADIONA, it was decided on two specific past launches which subsequently have been analyzed in detail and are presented in the chapter at hand. These two launches are subsequently called Sample 1 and Sample 2.

It was decided on these two launches because of their direction from French Guiana towards the northwest (Sample 1) and northeast (Sample 2), respectively. Both trajectories cross the very dense sections covered by airplanes over the North Atlantic Ocean, i.e. the North Atlantic Tracks (NATs); one on the North Atlantic Ocean's western side and the other on the eastern side. Hence, analyzing these two launches in detail with ADIONA provides a firm insight into the risks at hand and the probability of impact with an airplane in case of a launcher's accident, and debris falling back on airplanes. In this chapter these obtained results are presented and discussed using the previously defined date and time of the upper limit, i.e. the highest plane density derived in Chapter 3.

4.1. Results for sample 1 on 09/08/2021, 15:00 UTC

This section presents the results obtained with ADIONA for the launch of Sample 1.

4.1.1. Taches of sample 1

The obtained results and their visualizations are presented. As described in Chapter 3, the time instant of investigation has been chosen as 09/08/2021 at 15:00 UTC for Sample 1 due to the dense distribution of airplanes on the western side of the North Atlantic Ocean.

Fig. 5 and Fig. 6 present the taches in red color at time instances of 120 s and 326 s after lift-off. Additionally, Sample l's launch trajectory (dark green), the declared NOTAM zones (light

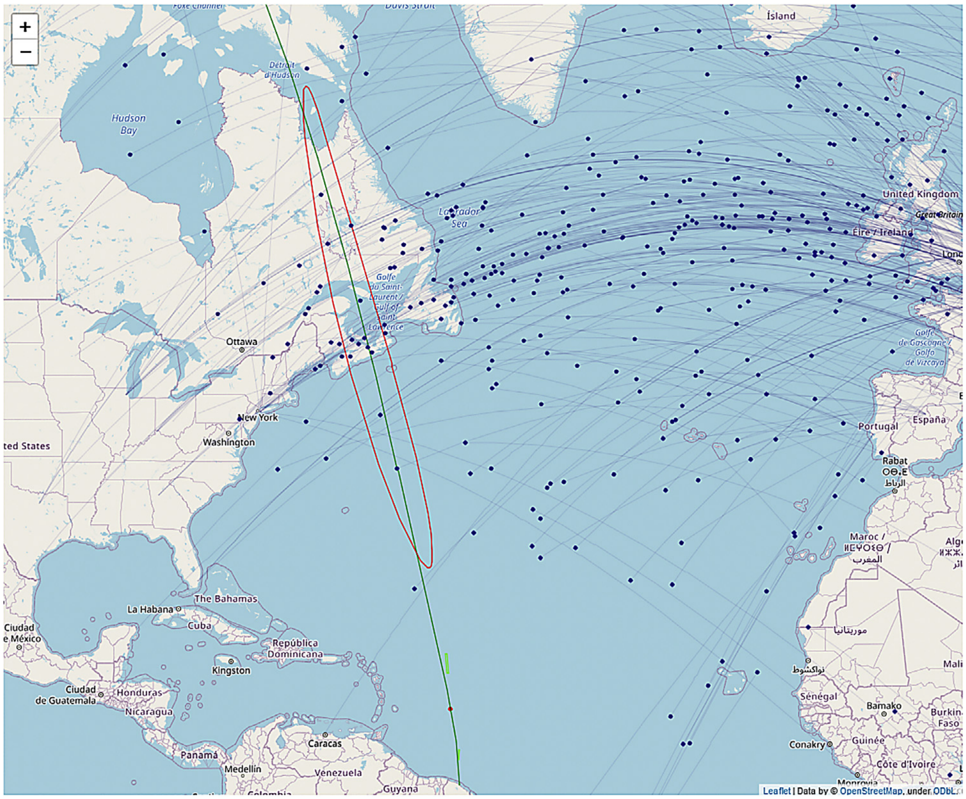

Fig. 6. Tache of Sample 1, 326 s after lift-off. The red contour line (the tache) represents the expected boundary of debris due to a launcher's explosion at the given time. The dark green line represents the rocket path, the red dot is the rocket's position at explosion, the light green rectangle is the NOTAM exclusion zone.

green), the current position of the launcher (red dot), as well as all the airplanes at their current estimated position (blue dots) and their trajectories (blue) are displayed.

4.1.2. Airplanes and people inside tache

In a next step, the number of airplanes inside the taches at the previously presented time instants has been analyzed. An estimate was made that the average number of passengers per airplane would amount to 350 people, on the basis of the FAA [18] which declared an estimate of 300 people as conservative. Consequently, the number of total people inside the tache at each time instant could be calculated.

Fig. 7 presents the distribution of the number of airplanes inside the taches and the number of people inside the taches at each time instant for Sample 1.

Shortly after launch no airplane was located inside the tache until a time instant of 280 s after lift-off, where two airplanes are located in the tache. From 292 s after launch onwards for every time step there is at least one airplane inside the tache. The maximum number of airplanes inside the tache was detected at 330 s after lift-off with a total number of 37 airplanes. This corresponds to a total number of 12′950 people inside the tache. The given set of data of taches ended at this time instant which is why the taches have not been simulated until a later point.

4.1.3. Probability calculation for sample 1

The desired output is the probability to hit one airplane in case a launcher explodes at a specific instant in time. As described by Bellucci et al. [5], debris with a surface bigger than 100 cm^2 causes fatality to an airplane. In this study, all pieces of debris have a bigger size than 100 cm^2. This fact has been exported from an internal CNES software which defined the size of debris fragments, and has therefore been used as a given input data in this study. The probability calculation was performed for the previously depicted time instants. The calculation was based on the following input data and performed for each time instant:

- Number of aircraft inside the tache
- Surface of the tache
- Number of debris with a bigger surface than 100 cm^2
- Size of the smallest debris
- Size of the total debris which falls back at specific time instant
- Surface of an airplane

The surface of each tache was approximated as an ellipse and its calculated surface was used for the probability calculation. The surface of each airplane was defined as 1150 m^2, considering the same size as described by Bellucci et al. [5].

To obtain the probability calculation, the following procedure has been used: The size of the smallest debris has been defined as the size of one "pixel". Thereafter, it was calculated how many such pixels cover a tache, how many pixels cover one airplane, and how many pixels are covered by all the airplanes inside the tache. The probability to hit one pixel could thus be calculated as well as the probability to hit one airplane.

Fig. 8 graphically presents the obtained results. Only the range of area of interest, i.e. 270 s after lift-off until 330 s after lift-off, which does not cover a probability of zero right after lift-off, is depicted.

Due to confidentiality reasons, the obtained probability cannot be published in precise numbers. The results and graph are presented in proportion to the risk boundaries set by the French Space Operations Act [24].

The probability of impact, and hence fatality according to Bellucci et al. [5], to one airplane in ratio to the safety margin limit set by the French Space Operations Act [24], to cause at least one casu-

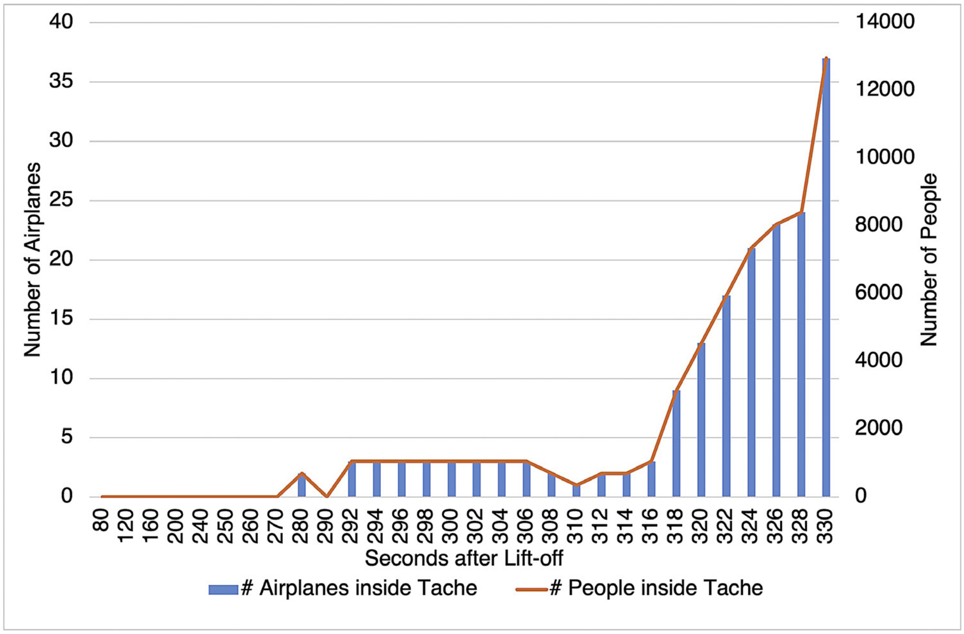

Fig. 7. Number of airplanes and people inside taches of Sample 1, on 09/08/2021, at 15:00.

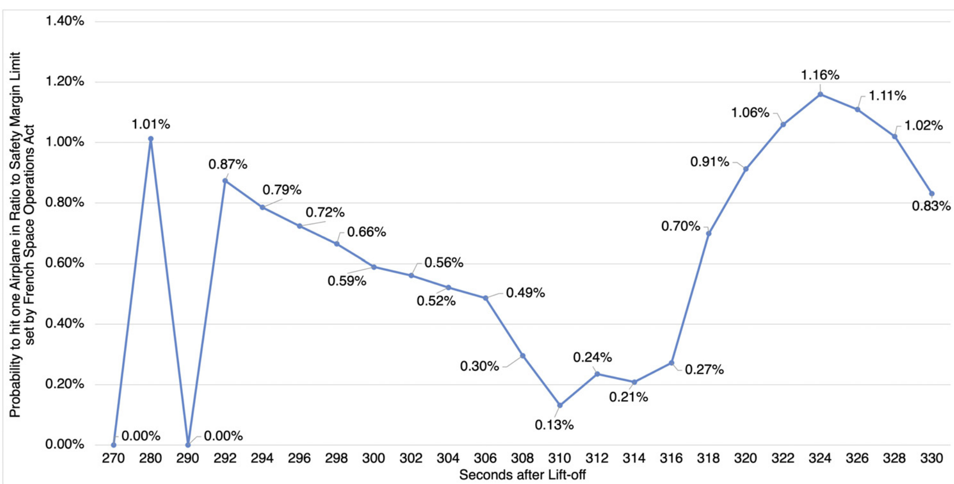

Fig. 8. Catastrophic Event: Probability of fatality to one airplane in ratio to safety margin limit set by French Space Operations Act, in case of explosion, Sample 1, on 09/08/2021, at 15:00.

alty (under the assumption that hitting one airplane consequently kills at least one person)

– which is defined as 2×10^{-5} – in case of explosion for Sample 1, on 09/08/2021, at 15:00 ranges from 0.13 % of the safety margin limit at 310 s after lift-off to 1.16 % of the safety margin limit at 324 s after lift-off.

4.2. Results for sample 2 on 09/08/2021, 13:00 UTC

This section presents the results obtained with ADIONA for the launch of Sample 2.

4.2.1. Taches of sample 2

The obtained results and their visualizations are presented. As described in Chapter 3, the time instant of investigation has been chosen as 09/08/2021 at 13:00 UTC for Sample 2 due to the dense distribution of airplanes on the eastern side of the North Atlantic Ocean.

Fig. 9 and Fig. 10 present the taches in red color at time instances of 354 s and 364 s after lift-off. Additionally, the declared NOTAM zones (light green) as well as all the airplanes at their current estimated position (blue dots) and their trajectories (blue) are displayed.

4.2.2. Airplanes and people inside tache

In a next step, the number of airplanes inside the taches at the previously presented time instants has been analyzed. The same estimate previously applied to Sample 1 was made that the average number of passengers per airplane would amount to 350 people. Consequently, the number of total people inside the tache at each time instant could be calculated.

Fig. 11 presents the distribution of the number of airplanes inside the taches and the number of people inside the taches at each time instant for Sample 2.

Shortly after launch no airplane was located inside the tache until a time instant of 350 s after lift-off where one airplane is located in the tache. From 358 s after launch onwards for every time

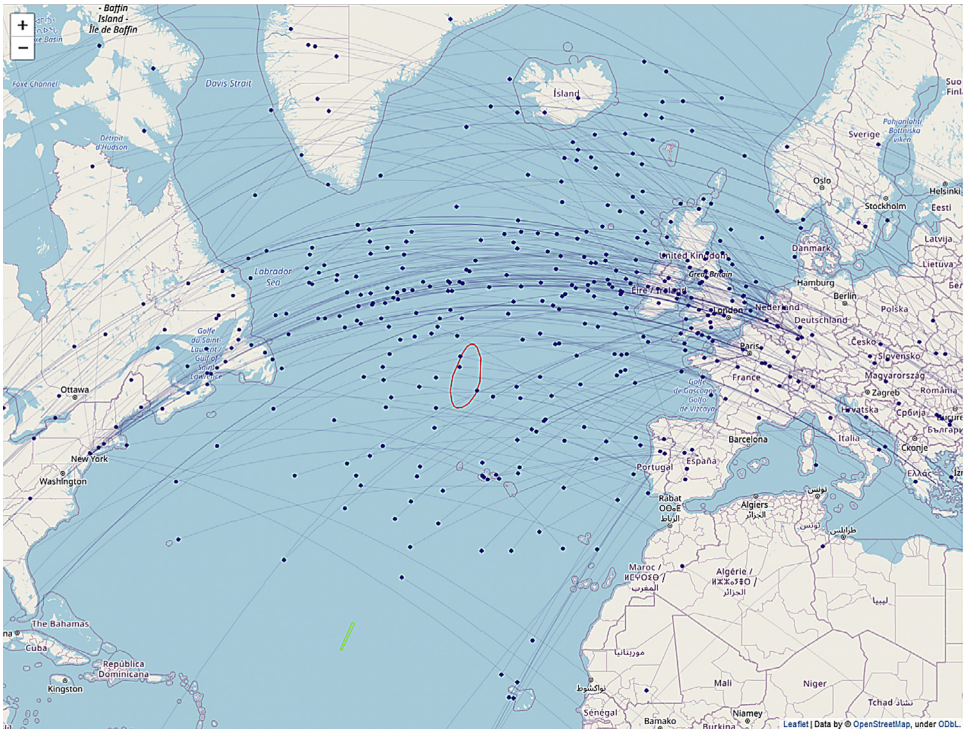

Fig. 9. Tache (red contour) of Sample 2, 354 s after liftoff (09/08/2021, 13:00 UTC). The small light green rectangle at the bottom of the plot is a declared NOTAM zone.

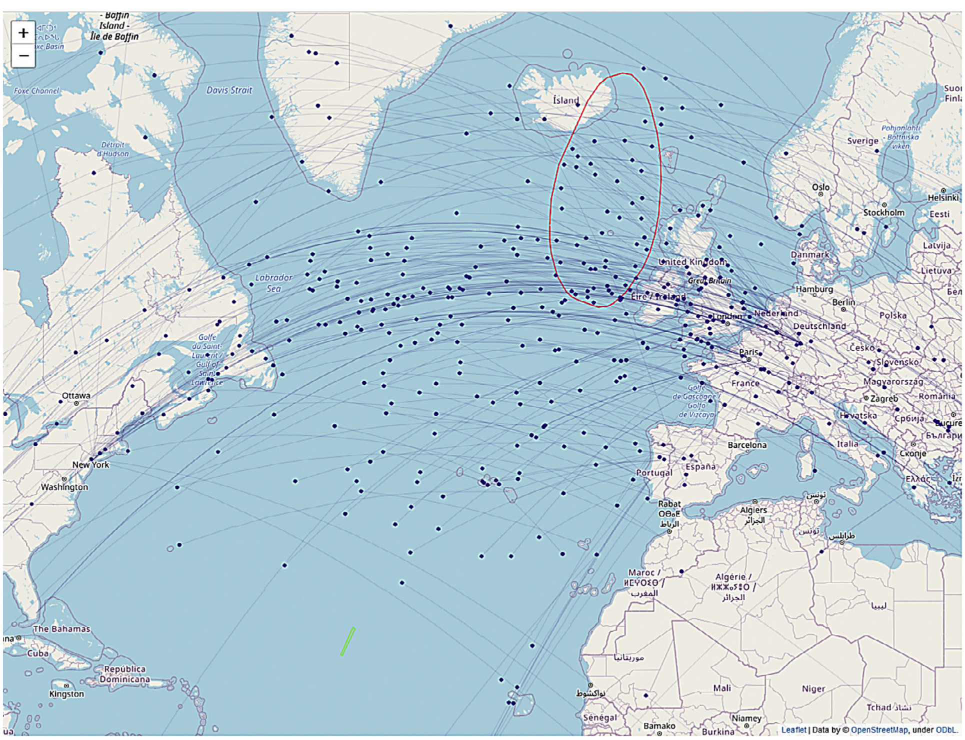

Fig. 10. Tache (red contour) of Sample 2, 364 s after liftoff (09/08/2021, 13:00 UTC).

step there is at least one airplane inside the tache. The maximum number of airplanes inside the tache was detected at 364 s after lift-off with a total number of 46 airplanes. This corresponds to a total number of 16′100 people inside the tache. The set of data of taches ended at the time instant of 368 s after lift-off which is when the tache was outside of the area densely covered by airplanes over the North Atlantic Ocean's eastern side.

4.2.3. Probability calculation for sample 2

The desired output is the probability to hit one airplane in case a launcher explodes at a specific instant in time. As described by Bellucci et al. [5], debris with a surface bigger than 100 cm^2 causes fatality to an airplane. In this study, all pieces of debris have a bigger size than 100 cm^2. This fact has been exported from an internal CNES software which defined the size of debris fragments, and has

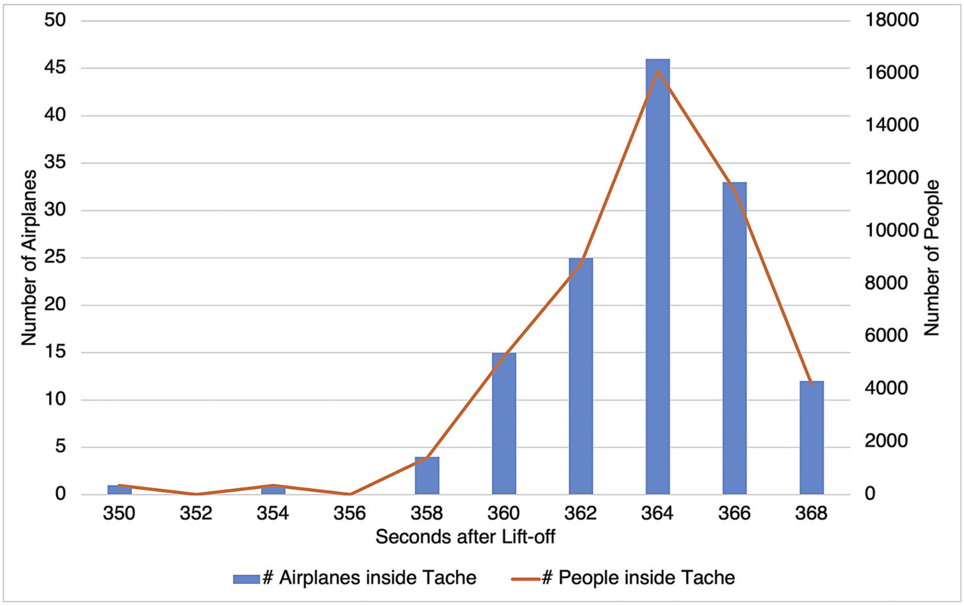

Fig. 11. Number of airplanes and people inside taches of Sample 2, on 09/08/2021, at 13:00.

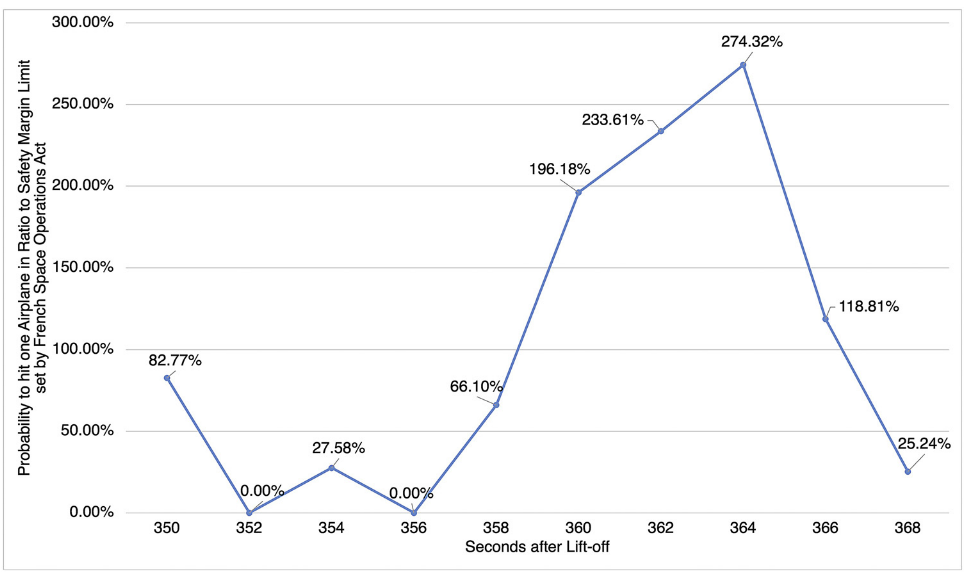

Fig. 12. Catastrophic Event: Probability of fatality to one airplane in ratio to safety margin limit set by French Space Operations Act, in case of explosion, Sample 2, on 09/08/2021, at 13:00.

therefore been used as a given input data in this study. The probability calculation was performed for the previously depicted time instants. The calculation was based on the following input data and performed for each time instant:

- Number of aircraft inside the tache
- Surface of the tache
- Number of debris with a bigger surface than 100 cm^2
- Size of the smallest debris
- Size of the total debris which falls back at specific time instant
- Surface of an airplane

The surface of each tache was approximated as an ellipse and its calculated surface was used for the probability calculation. The surface of each airplane was defined as 1150 m^2, considering the same size as described by Bellucci et al. [5]. The probability calculation has been conducted using the same methodology as for Sample 1.

Fig. 12 graphically presents the obtained results. Only the range of area of interest, i.e. 350 s after lift-off until 368 s after lift-off, which does not cover a probability of zero right after lift-off, is depicted. Due to confidentiality reasons, the obtained probability cannot be published in precise numbers. The results and graph are presented in proportion to the risk boundaries set by the French Space Operations Act [24].

The probability of impact, and hence fatality according to Bellucci et al. [5], to one airplane in ratio to the safety margin limit set by the French Space Operations Act [24], to cause at least one casualty (under the assumption that hitting one airplane consequently kills at least one person)

– which is defined as 2×10^{-5} – in case of explosion for Sample 2, on 09/08/2021, at 13:00 ranges from 25.24 % of the safety margin limit at 368 s after lift-off to 274.32 % of the safety margin limit at 364 s after lift-off.

5. Conclusions

5.1. Conclusions on ADIONA and methodology

The new software ADIONA has been developed from scratch to assess the risks on world air traffic of debris' impact due to rocket explosions after launch. Real-world data on air traffic, provided by EUROCONTROL, and real-world data on rocket launches, provided by CNES, have been used and applied in ADIONA. The cohabitation of rocket launches from the Guiana Space Center and air traffic over the North Atlantic Ocean has been investigated.

Different sequences of these launches, Samples 1 and 2, have been analyzed in detail. The taches (hazard areas) at different time instants have been analyzed and visualized, the number of airplanes and hence people inside the tache at every analyzed time instant has been outlined, and the probability of impact with an airplane in case of the launcher's explosion and debris falling back on airplanes has been performed.

The newly established ADIONA software showed great performance and obtained precise results under the given input data. In the future, ADIONA can be applied to more rocket launches and airplane flights and could even be applied to geographical regions other than the North Atlantic Ocean.

The number of given input data was limited. The goal of the study was to develop a software and obtain the first results in the intersection of the space industry with rocket launches and the aviation industry with airplanes over the North Atlantic Ocean. The goals could successfully be reached. Eventually, the aim is to provide a basis for formulating policies to protect aircraft from debris from malfunctioning launchers.

5.2. Conclusions of results for sample 1

The results of Sample 1 and its probability calculation showed a probability of fatality to one airplane in ratio to the safety margin limit set by the French Space Operations Act in case of an explosion in a range from 0.13 % of the safety margin limit at 310 s after lift-off to 1.16 % of the safety margin limit at 324 s after lift-off. These numbers are significantly high and a further investigation with fine tuning of the risk parameters is recommended.

5.3. Conclusions of results for sample 2

The results of Sample 2 and its probability calculation showed a probability of fatality to one airplane in ratio to the safety margin limit set by the French Space Operations Act in case of an explosion in a range from 25.24 % of the safety margin limit at 368 s after lift-off to 274.32 % of the safety margin limit at 364 s after lift-off. These numbers are significantly high and a further investigation with fine tuning of the risk parameters is recommended.

The results show a considerable high risk to world air traffic in case of a rocket explosion after launch.

The results obtained with ADIONA emphasize the risk analysis on air traffic's high importance. It is concluded that the cohabitation of space and air traffic and the probabilistic risk assessment thereof is important to be monitored to eventually be diminished. It is recommended to invest further resources into this observation. Further investigations should take place on this probabilistic risk analysis, considering more details and fine-tuning in the risk calculation and assessment method.

The results and the development of ADIONA build a firm foundation and enable future calculations and further development of risk analysis of launch and reentry mishaps on world air traffic and will enable future investigations at any geographical area in the world.

6. Outlook

It is recommended, in a next step, to obtain taches at flight level, and not at sea level. This would probably require deep coding adjustments in CNES' accidental explosion simulation software to extract taches at different heights. Additionally, it is recommended to collect more detailed input data to further reduce the 2.99 percent of error in estimated aircraft position. Also, in a next step a graphical user interface could be implemented, and the simulation could be coupled to live flight data.

In the further future, efforts should be made to eventually reduce the risks pointed out with ADIONA. One suggestion is to implement mitigations, such as enhancing the reliability of rockets. Additionally, real-time procedures could be developed to promptly alert air traffic bodies, including Civil and Military Aviation Authorities and Air Navigation Service Providers, about the precise position and geometry of refined hazard areas following an explosion event. Both the Federal Aviation Administration (FAA) in the US, through its SDI initiative, and EUROCONTROL in Europe, with its ECHO 2 project, are actively pursuing initiatives in this direction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Nathalie Nick: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **Léonard Buchaillot:** Conceptualization, Resources, Project administration.

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