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A Dynamic Debris Hazard Corridor for Space and Air Traffic Management

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Abstract

The airspace is a national asset shared by a multitude of users, including aircraft, drones, and spacecraft. Regulating airspace usage among various stakeholders has traditionally been achieved through the segregation of different operations. This approach was effective when the airspace was primarily allocated for air traffic, and spacecraft and other users were relatively rare. However, with the growing volume of both air traffic and space activities, there is now an urgent need to develop new dynamic and adaptative strategies for ensuring the safe and efficient sharing of airspace among diverse stakeholders. For instance, a timely dynamic strategy, which takes into account the real-time status and progress of the spacecraft and adapts to the associated risks, could facilitate efficient airspace sharing.

Space launch activities have recently experienced tremendous growth with the development of commercial space launch. In this context, the current airspace management strategies, including space transition corridor, and temporary flight restriction, have demonstrated their effectiveness in various space launch operations. Nevertheless, these methodologies do require a higher level of familiarity with space launch operations and advanced capabilities. They can also tend to be overly conservative, considering only a limited set of factors. In addition, as space missions continue to grow and air traffic demand increases, airspace closures are capable of ensuring safety, but can lead to extensive rerouting, delays, reduced airport accessibility, and constrained nearby airspace utilization.

In this study, we develop the Dynamic Debris Hazard Corridor (DDHC) as a novel concept, offering the potential to bridge the gap between traditional and emerging needs. The primary objective of this study is to compare the traditional, conserved approach of airspace closure with a proposed dynamic method that involves the sequential release of convex hull segments in the Dynamic Debris Hazard Corridor (DDHC). Unlike conventional approaches, the DDHC is ideally suited for managing dense air traffic. The findings indicate that the dynamic management of the DDHC can potentially reduce disruptions in air traffic without compromising safety. Computational results have demonstrated that, out of 37 flights, 5 did not undergo rerouting thanks to the proposed DDHC methodology. Additionally, for the flights that did undergo rerouting, the system reduced the rerouting distance by 1471.45 km compared to the currently used airspace closure protocol.

Keywords: space traffic; air traffic; dynamic space hazard corridor; hazard zone; safety; efficiency.

1. Introduction

Airspace serves as a shared resource accommodating a variety of users, including both spacecraft and aircraft. In current operational procedures, a significant portion of the airspace enveloping the anticipated trajectory of a spacecraft during its ascent and recovery phases is reserved for an extended duration **(1)**. This reserved airspace serves as a protective buffer, aiming to mitigate the risks associated with space activities. It balances the need for safety with the economic implications of air traffic. This trade-off remains tolerable when space missions are infrequent. However, with the growing prevalence of commercial space activities, there arises a need to explore more efficient solutions that minimize their impact on air traffic while maintaining safety standards. To ensure the safety of other airspace users, space operations were segregated from the air traffic and were usually carried out in designated Special Activity Airspace (SAA) **(2) (3)**

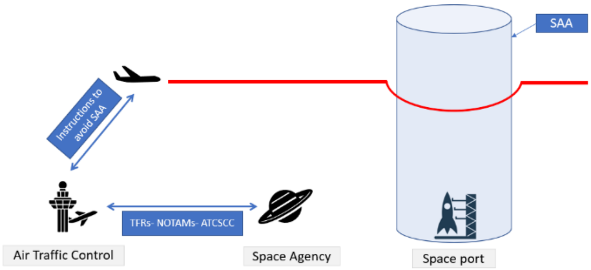

Figure 1: Segregation of space activities from nominal air traffic.

During space operations, air traffic is rerouted around the designated SAA to ensure their safety, as illustrated in Figure 1. The relevant federal space agencies collaborate with affected Air Traffic Control (ATC) centers to implement measures for the restriction and management of airspace expected to be impacted by the space operation. This coordination involves the utilization of Temporary Flight Restrictions (TFRs), Notices to Airmen (NOTAMs), and Air Traffic Control System Command Center (ATCSCC) Advisories (4).
Historically, due to the infrequency of these space operations and their classification as matters of national importance, there existed limited motivation to enhance the efficiency of these complex processes concerning their effects on the overall efficiency and capacity of the airspace system.
In light of the recent surge in space launches, a corresponding increase in the number of space providers, including private entities such as Blue Origin, SpaceX, and Virgin Galactic, has been observed. As the landscape of commercial space activities continues to broaden, it becomes imperative to undertake research initiatives aimed at developing new architectural frameworks, tools, and procedures. The objective is to ensure the safe and efficient integration of the escalating number of launches into the airspace system (5).

The Main challenge in efficiently integrating space launch activities with conventional airspace lies in the available communication, navigation, and surveillance capabilities. These capabilities play a pivotal role in ensuring operational efficiency and safety in the management of both air and space traffic, as highlighted in previous studies (6) (7). To address this challenge, the Federal Aviation Administration (FAA) has recently developed and tested the Space Data Integrator (SDI) system. The primary objective of the SDI system is to enhance airspace integration by automating situational awareness, improving the monitoring of vehicles in the airspace, and enabling more effective detection and response to off-nominal scenarios, as discussed in the (8). These aforementioned capabilities are essential for advancing the implementation of mixed airspace, accommodating diverse airspace users.

The present study leverages the capabilities of the SDI system and introduces the Dynamic Debris Hazard Corridor (DDHC) as an innovative concept aimed at meeting the evolving demands in integrating space launch activities with the national airspace system. DDHC consists of a sequential release of convex hull segments of airspace based on the spacecraft's progression. The primary objective of DDHC is to establish a balanced harmony between safety considerations and operational efficiency. Conceptually, DDHC functions as a dynamic hazard zone strategically designed to mitigate the exposure of aircraft to risks associated with space launch operations, while concurrently refining the dimensions and duration of airspace closures to optimize operational efficiency. The formulation of DDHC encompasses various procedural elements, including trajectory analysis and debris modelling.

2. Space Traffic Management: Current Operation and proposed approach

For the management of current space operations, a common practice involves subdividing the process into three distinct phases (9) (10). These phases consist of the strategic phase, the tactical phase, and the post operation phase. A concise overview of the most pertinent contents within each phase is provided below:

- The strategic phase necessitates effective coordination and collaboration to ensure the safety of operations while addressing the interests of all stakeholders through Collaborative Decision Making (CDM). Furthermore, a standard and crucial procedure involves conducting risk assessments and identifying hazard areas for both nominal and non-nominal mission operations prior to submitting the application proposal. Subsequently, air traffic impact assessments are carried out, and an optimal operational timeframe is selected, taking into consideration the potential effects on all involved parties. Additionally, common practices include the establishment of Letter of Agreements (LOAs) and the precise definition and communication of Notices to Airmen (NOTAM).
- During the tactical phase, air traffic control (ATC) adjusts aircraft routes as necessary prior to the commencement of the mission. Typically, a shared situational awareness is maintained through hotline communication and information exchange. In this context, the spacecraft operator assumes responsibility for monitoring the spacecraft and disseminating pertinent information regarding its status and events to connected stakeholders. The main challenge currently encountered during the tactical phase is the lack of real-time information for aviation sites, which is due to the manual and non-automated methods presently in use. To address this challenge in future operations, the implementation of digitized measures is recommended to mitigate latency and reduce error susceptibility, thereby enhancing overall efficiency, particularly in non-nominal event scenarios. For non-nominal operations, various safety measures are employed, including the implementation of continuous airspace closure, the calculation of collision hazard areas and their distribution in the event of an incident, and the recalibration and distribution of high-risk areas based on the latest state vector. ATC then reroutes affected air traffic accordingly.
- Post operations analysis typically involves the comparison of planned and actual data. In some countries such as the United States and the United Kingdom, a comprehensive assessment is conducted to evaluate the actual impact of the mission on the airspace system and aviation. Additionally, lessons learned and best practices are extrapolated, and these insights are meticulously documented in reports disseminated among pertinent stakeholders, intended for incorporation into future operational considerations.

The research herein presented focuses on the strategic phase, and experiments with the application of the model during the tactical phase. The primary aim is to calculate Debris Hazard Areas (DHAs) at a strategic level and release them in real-time based on the spacecraft's progression. This ensures the simultaneous enhancement of safety and operational efficiency, particularly in its impact on air traffic. The proposed methodology is beneficial for countries with limited experience in space launch activities. It aids in maintaining safety levels by keeping airspace with potential risks closed. Simultaneously, it facilitates more efficient operations by releasing safe airspaces as the spacecraft progresses.

Currently, the computation of DHAs is a widely adopted practice in various countries, including the United States, the United Kingdom, France, and Japan (11). Despite this commonality, individual countries exhibit distinct best practices and policies in implementing DHAs during the tactical phase.

In the case of the United States, a highly effective strategy is employed wherein DHAs are calculated at the strategic level based on failure predictions along the spacecraft trajectory (11)**.** These calculated DHAs are communicated to different stakeholders prior to the mission, only being activated if a failure is detected during the tactical phase. This approach reflects a flexible and efficient methodology, leveraging the U.S.'s extensive experience in space launch operations and its confidence in promptly addressing failures as they occur. Conversely, the United Kingdom employs a more conservative approach (12)**.** In this instance, calculated DHAs are activated as a precautionary measure during the space launch tactical phase, even in the absence of detected failures. This cautious approach is chosen by the UK, which, due to limited experience in such operations, opts for heightened vigilance, resulting in extended closures of affected airspace.

It is believed that realizing the level of flexibility and efficiency embraced by the United States necessitates the possession of extensive experience in space launch operations. This poses a challenge for countries new to this domain. Meanwhile, the conservative approach adopted by the United Kingdom could be enhanced through the introduction of a protocol for partial airspace closure, as proposed herein and referred to as the Dynamic Debris Hazard Corridor (DDHC). This protocol depends on spacecraft trajectory profile, and predicted debris distribution, thereby establishing a balanced trade-off between safety considerations and operational efficiency in such operations. The concept diagram of the proposed approach is highlighted in Figure 2.

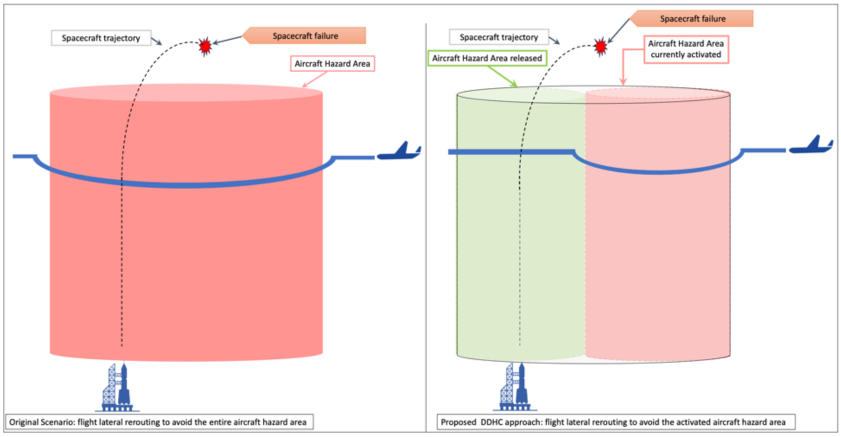

Figure 2: Concept diagram of the proposed DDHC. In the conventional approach, flights are rerouted to avoid the entire affected airspace, known as the Aircraft Hazard Area. The DDHC concept suggests implementing a partial airspace closure and the timely release of airspace that no longer poses a threat to the air traffic.

It presents a schematic comparison between the traditional approach and the DDHC proposed in the current paper. Under the traditional approach, flights are redirected to avoid the entirety of the affected airspace, commonly designated as the Aircraft Hazard Area. The DDHC concept proposes the adoption of a partial airspace closure strategy, coupled with the timely release of airspace segments that cease to present a threat to air traffic.

3. Dynamic Debris Hazard Corridor Methodology:

Implementing the suggested Dynamic Debris Hazard Corridor (DDHC) entails a series of steps that are outlined in Figure 3. It highlights the process involved in the generation of DDHC which includes simulation of the spacecraft trajectory and generation of debris hazard areas. Then, the impact of DDHC on air traffic has been assessed through real-time simulation using ADS-B flight data. Finally, the real-time simulation yields results on the number of flights that need to be rerouted and the additional distance flown.

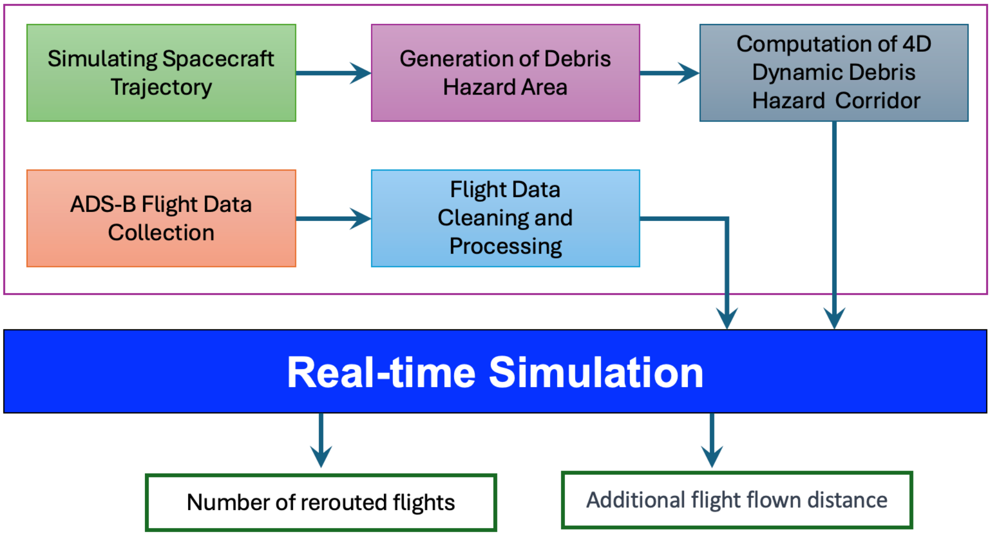

Figure 3.Dynamic Debris Hazard Corridor Methodology Framework

The process involved in the generation of DDHC is highlighted below:

- Modelling the spacecraft trajectory: This initial step involves the mathematical modelling of a two-stage spacecraft as detailed in (13). Using astrodynamics principles, this model considers various factors such as gravitational acceleration and atmospheric drag.
- Debris area calculation: Knowledge of debris hazard regions would enable the ATCs to guide the affected aircraft aways from the hazard area. Building upon the spacecraft trajectory model, this step focuses on the estimation of the extent of the airspace containing falling debris due to a spacecraft breakup. In this study, a spherical rotating Earth is assumed, the propagation of debris is calculated at 20-second intervals along spacecraft's nominal trajectory, and the debris initial state vector is defined as the point that spacecraft breakup. A sample debris propagation trajectory at time 310 seconds is illustrated in Figure 3. The figure highlights how debris are propagated when a failure occurs. This shows that the debris are distributed over a very large area, potentially exceeding two degrees in latitude and 1.5 degrees in longitude. This results in a significantly extensive airspace that should be closed as a precautionary measure during space launch activities.

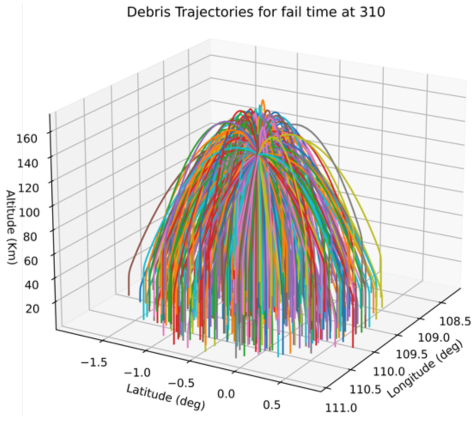

Figure 4: Example of debris propagation at time step t=310 sec.

The equations of motion to estimate debris dispersion considers the gravitational force, drag force and angular force as detailed in (14).

- Generation of debris hazard area: In this step, Kernel Density Estimation (KDE) is used to calculate the spatial location distribution of debris on the ground, and a pre-defined density threshold is chosen to generate the contour boundary, so as to define the Debris Hazard Area boundary. This step maps out regions of airspace that present probability of collision with debris.
- Computation of the Dynamic Debris Hazard Corridor: The final step involves the generation of a KDE contour of the Debris Hazard Area at every 20 seconds interval along the spacecraft's nominal trajectory. These contours, each defining a segment of debris distribution at specific time interval, are sequentially constructed to form a continuous three-dimensional convex hull. And the altitude of the overall convex hull is determined by the maximum altitude reached by any debris throughout all the time steps. For a conservative approach, the overall continuous convex hull, composed of these individual contour segments, is predefined prior to launch. Once defined, the airspace remains closed during the tactical phase as shown in Figure 4, until the estimated last debris falls to the ground.

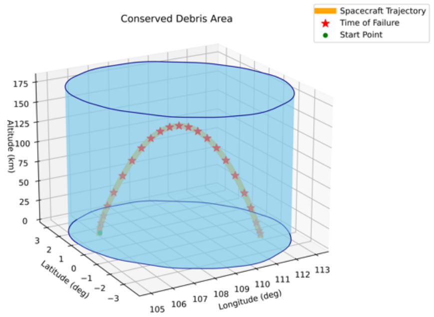

Figure 5: Conservative Debris Hazard Areas. Generated upon spacecraft's nominal trajectory at 20-second interval, the entire corridor is activated during the space launch tactical phase.

This pre-defined area ensures that the airspace enveloped within it remains clear of aircraft during launch. In this study, it suggests the sequential release of individual hull segments. Each segment's definition is threefold: its altitude, its dimensions, and its time duration. As illustrated in Figure 6, the altitude for each segment is determined by the highest point that debris can reach within that specific time interval; the size of each segment is defined by the contours generated from any two consecutive time steps, together forming a section of the convex hull for that duration. Figure 6 illustrates the state of the debris corridor at time t = 230 sec and each segment of the corridor is sequentially released as the spacecraft progresses past the corresponding time interval. Meanwhile, the remaining parts of the overall convex hull, as initially defined, continue to be activated.

Such strategy allows for a dynamic adaptation to the evolving conditions of the spacecraft's trajectory and debris dispersion. By sequentially releasing segments of the convex hull, airspace can be progressively reopened, minimizing disruptions to air traffic while maintaining the concern for safety.

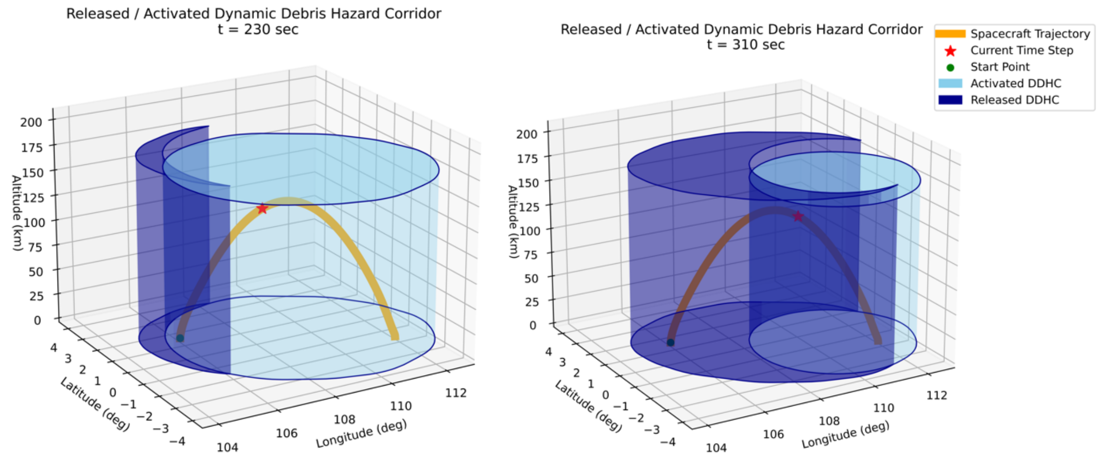

Figure 6: Sample Dynamic Debris Hazard Corridor with sequential segment release strategy at time = 230 sec and time = 310 sec. Each segment is released in sequence as the spacecraft surpasses the corresponding time step. The segments depicted in light blue remain closed, while the segment in dark blue represents the airspace that is released.

4. Computational Results:

This section provides comparative analysis between the conserved approach and proposed method for managing the airspace closure and release during space launch tactical phase. The primary metric for this comparison is the calculated number of aircraft impacted. The traffic data that covers from UTC 02:30 to 03:00 and includes 683 aircraft in Southeast Asia on 14^{th} Dec 2023 is used for the evaluation. The study simulated 300 debris pieces at each 20-second interval along the spacecraft's nominal trajectory. These debris pieces were characterized a heading perturbation to follow a normal distribution $U(0,180)$, an angle perturbation to follow a normal distribution $U(0,360)$, and a velocity perturbation following uniform distribution $U(0,100)$, offering a potential representation of debris dispersion scenarios.

- Conserved approach evaluation: The conserved approach involves maintaining a fixed debris hazard corridor throughout the launch phase. This hazard corridor consists of a fusion of every potential hazard area at every spacecraft stage along its trajectory. The duration of the airspace closure is 509 seconds during the tactical phase. This resulted in 37 flights being affected, with a total rerouting distance of 12272.82 km. The rerouting distance is calculated in comparison with the actual flown distance collected from historical data.

- Proposed approach evaluation: The proposed approach introduces a dynamic management of the DDHC, releasing segments of the convex hull sequentially, based on the spacecraft's progression. The study computes the potential impact on number of aircraft using the same methodology but adjusts based on the reduced duration and extent of airspace closures due to the phased release of convex hull segments. This approach reduced the number of affected flights to 32, with a rerouting distance of 10801.37 km.

The results suggested that 5 flights have benefit from implementing the DDHC and have not been rerouted. Also, led to a decreased rerouting distance, a total of 1471.45 km, for these flights. This reduction underscores the method's efficiency in optimizing airspace utilization, reducing the need for extensive rerouting that often result from conserved airspace closures. The proposed approach highlights the potential for more flexible and less disruptive integration of space launch operations within existing air traffic systems.

5. Conclusions:

The research presented herein constitutes a preliminary study aimed at evaluating the advantages of implementing a Dynamic Debris Hazard Corridor to seamlessly integrate space launch activities into air traffic. The proposed approach aims at ensuring a harmonious balance between the safety and efficiency of space launch operations.

Initially, a conservative strategy involving the closure of a substantial portion of airspace is employed. Subsequently, as the spacecraft starts moving, specific segments of the airspace are gradually activated. These activated zones are determined through the calculation of the debris hazard area at each potential location along the spacecraft trajectory.

The findings underscore the potential benefits of adopting a flexible approach, such as the Dynamic Debris Hazard Corridor, for managing debris hazards. This approach has the capacity to enhance both the efficiency and safety of airspace utilization, effectively addressing the needs of both space launch activities and commercial aviation.

Future works should evaluate the possibility of applying the DDHC at tactical phase. This involves accurate and reliable communication between space launch operator, ATCs and pilots.

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