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Uncontrolled Re-entry Risk for Aviation and the benefits of real time information services

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Abstract

The increasing number of satellites and space debris reentering Earth's atmosphere poses significant challenges to aviation safety, particularly due to the unpredictability of uncontrolled reentries. With the rapid growth of satellite constellations, these events are expected to increase, and despite advancements in tracking systems and controlled reentry technologies, many reentries remain difficult to predict. While real-time monitoring tools such as the U.S. Space Data Integrator (SDI) and Europe's SpaceTrack offer critical support for Air Navigation Service Providers (ANSPs) to manage debris events, a gap persists in addressing the hazards posed by uncontrolled reentries. The main challenge lies in the timing and precision of reentry predictions. Current hazard areas are often too large to manage effectively. The size of the hazard area combined with the uncertainty of location can lead to unnecessary airspace closures and widespread disruption of global air traffic, which in turn compromises aviation safety. A notable example is the November 2022 uncontrolled reentry of a Chinese Long March 5B rocket stage, which resulted in airspace closures across Europe, even though the debris ultimately landed in the Indian Ocean. Accurate reentry trajectories and hazard zones can typically only be pinpointed minutes before the event, leaving limited time for authorities to respond. Real-time data provision during the final moments of reentry is critical for improving the accuracy of hazard area predictions, enabling timely updates to affected airspace regions. This can ensure aviation safety without unnecessarily closing or evacuating large areas of airspace. By integrating real-time hazard information, advanced reentry prediction tools, and robust communication methods, the aviation sector can mitigate risks while minimizing operational disruptions. The presentation will demonstrate the essential mechanisms and services through which real-time data provision can support and maintain aviation safety, considering the global and cross-border nature of debris mitigation efforts. It will also address the need for interoperable, internationally harmonized procedures to manage uncontrolled reentries effectively.

1. Introduction

The second space race is underway, ushering in a new era in space travel, exploration, economic opportunity, and technological development. Rapid advances in manufacturing, technology, and vehicle reusability are fueling this renaissance in space activity and driving a sharp increase in global launch and reentry cadence.

Dramatic reductions in cost of both payload and transit of payload to space are bringing opportunities within reach of commercial operators that once were the sole purview and domain of nation states. This basic shift, from nation state to private and commercial entities has introduced significant innovation in launch and reentry operations requiring paradigm shifts away from legacy norms and standards to keep pace with demand while maintaining efficiency and safety.

A significant contributor to the increased cadence is the growth of satellite constellations in Low Earth Orbit (LEO, defined as an orbit altitude below 2.000 km) that provide for greater system diversity and redundancy, increasing the resiliency of orbiting satellite systems. Historically, satellite systems consisted of large monolithic systems often positioned in Geo Stationary orbits. These complex systems required years of development, significant financial investment, and lacked system redundancy. Technological advances have greatly reduced the cost, complexity and size of satellite systems allowing for mass production and easier lift capability. The ability to launch and deploy constellations at a cost achievable by industry has led to rapid innovation in low earth orbit. These highly resilient systems are designed to operate in extreme low earth orbit, maintain full operations after the loss of individual satellite(s), and operate with high bandwidth and low latency. This is a transformational shift in the operation of satellite systems in earth orbit.

In 2020, there were 2500 active satellites in earth orbit. As of 2024, there are an estimated 10,000 active satellites in orbit, a 300% increase over 2020 [13]. The space object catalog is maintained by the United States Space Force at the Joint Combined Space Operations Center (CSpOC) at Vandenberg Space Force Base. The catalog includes active and inactive satellites and space debris and is critical to the management of systems in earth orbit and determining reentry potentials.

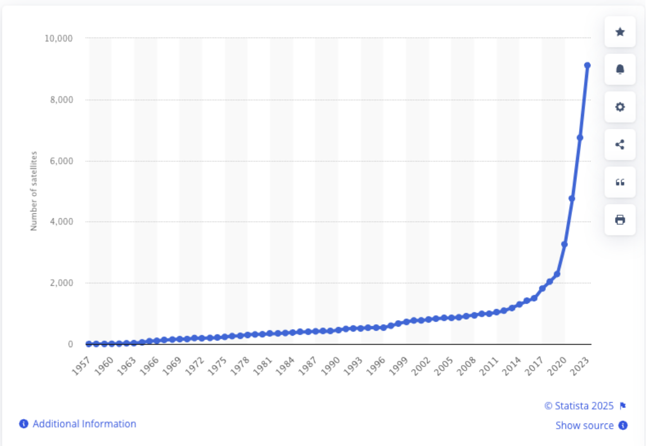


Figure 1: Growth of active satellites over time (1957-2023; Source: Statista, 2025)

The growing congestion in space (Figure 3), especially in LEO, have led to industry recommendations for best practices for space sustainability, including the planned deorbit of systems in lieu of leaving inactive systems in orbit. These best practices and planned obsolescence strategies for operational satellite systems are necessary due to the increasing launch cadence and by association the reentry cadence. The chart below (Figure 2) depicts the "hockey stick" growth of reentries in recent years as this begins to play out in real time.

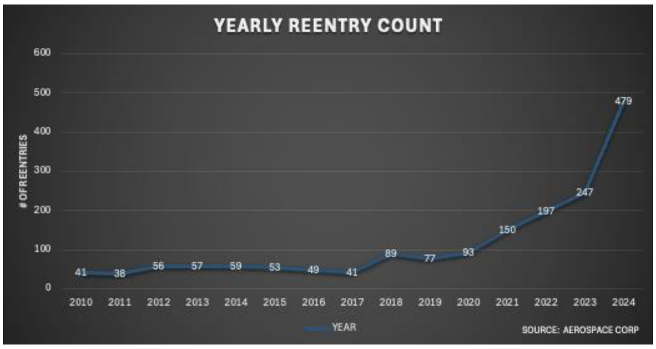


Figure 2: Number of reentries per year (Source: Aerospace Corporation)

The Federal Aviation Administration's (FAA) report to the United States Congress titled: Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit [1], dated September 23, 2023, estimates: ***"By 2035, if the expected large constellation growth is realized and debris from Starlink satellites survive reentry, the total number of hazardous fragments surviving reentries each year is expected to reach 28,000…"***

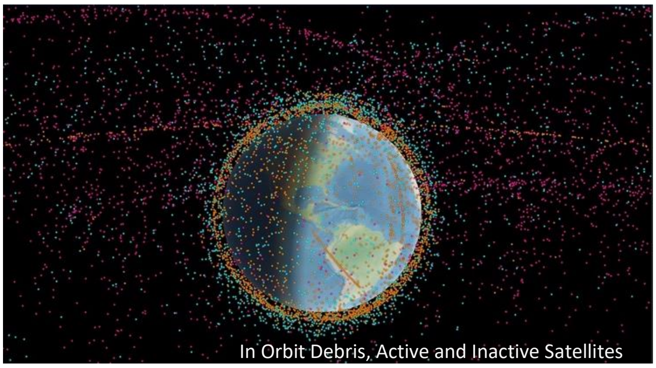


Figure 3: Visualisation of current distribution of man-made objects in space (Source: https://app.keeptrack.space/)

The rapid increase in both launch and reentry operations is stressing legacy procedures and processes for the integration of operations into global terrestrial airspace systems and is demanding innovation to solve the challenges. Safe and efficient integration of space launch and reentry operations into and through airspace systems around the world is paramount to the community of Air Navigation Service Providers (ANSPs).

2. Background

2.1. Reentry types

Objects in LEO are subject to gravitational forces and atmospheric drag, resulting in the eventual orbital decay and reentry into the earth's atmosphere. Reentries can generally be classified as controlled or uncontrolled reentries. Both of these types of reentries may or may not produce debris that is a risk to aviation:

- **Controlled or uncontrolled reentries with no significant debris surviving the reentry of the object.** These are reentries are designed for the object to break up with an atmospheric demise on reentry, with no significant debris survival. These reentries do not exceed risk thresholds to aviation obviating the need to protect airspace during the reentry. There is significant work and focus on the manufacturing of future systems to operate in this manner.
  An example of this type of reentry is the controlled reentry of the Northrup Grumman Cygnus spacecraft that carries payload to and from the International Space Station. On return to earth the vehicle and cargo are designed to completely burn up in the atmosphere on reentry.

- **Controlled reentries with significant debris surviving the reentry of the object.** Operators often reenter objects from space in a controlled manner that allows for a planned break up as atmospheric forces act on the vehicle. Some debris will survive reentry forces and impact on the earth’s surface in a planned and predictable manner. Also included in the category are spacecraft designed to survive reentry intact for recovery, i.e. SpaceX Dragon spacecraft. Risk assessment is performed for these operations and risk is mitigated by reentry location selection and notification of effected stakeholders. These reentries are generally planned for and conducted in remote locations mitigating safety risks. An example of this type of reentry is the upper stage of a Falcon 9 reentering the atmosphere after deploying payload. Below is an example of an upper stage reentry. Of note is the length of the hazard area, extending for several thousand kilometers.

Figure 4: Hazard area of a planned controlled Falcon 9 upper stage reentry (Source: FAA)

- **Uncontrolled reentries with significant debris surviving the reentry of the object.** These reentries produce debris that survives reentry forces with no effective capability for risk mitigation to uninvolved parties, including aviation. Because the reentry is not controlled, the reentry location is dictated by atmospheric forces offering location uncertainty and difficultly predicting and protecting for debris fields. As in the previous case, the notional debris dispersion and hazard area can be very large. Areas of high population and air traffic density are of particular concern. Risk is largely mitigated by the Earth’s surface being seventy percent ocean. As an additional risk mitigation method design for demise techniques are researched either aimed at reducing the surviving mass and/or the total number of fragments [24].

  Section 4 of this paper is looking into the uncontrolled reentries of Chinese Long March 5B rocket bodies that are an example of this type of operation and the associated risk.

2.2. Reentry related risk to aviation

As the number of objects in space increases, the number of uncontrolled reentries will continue to grow, raising global concerns regarding the risk to the uninvolved public. Of particular concern is the risk to the aviation community. Airframes in flight are particularly vulnerable to even small debris that, if encountered in flight, may endanger aircraft airworthiness and those on board. Several recent high-profile events have accentuated the concern and the need for improved safety capabilities to reduce the risk to the uninvolved public. The challenges associated with unplanned reentries were illuminated in the Federal Aviation Administration’s report to the U.S. Congress in September 2023 [1].

Air Traffic Control (ATC) units managed by ANSPs are charged with the management of operations within the airspace systems around the globe. A key piece of launch and reentry operations is the risk assessment of the mission and the potential risk to the uninvolved public. Risk assessment includes the calculation of risk to individuals in the air, on land, and at sea. The result of the risk assessment is the production of hazard areas that act as exclusionary zones or areas where uninvolved activity is restricted. ANSPs and the air traffic controllers within those ANSPs are charged with managing activity in the vicinity of Aircraft Hazard Areas (AHAs). The AHAs are also publicly advertised through the publication of Notices to Air Missions (NOTAMs) requiring sufficient lead time to effectively be incorporated into route planning. Aviation operators and air traffic controllers work in concert to ensure that aircraft are routed and kept from entering AHAs.

2.3. Existing Solutions

Objects in space are tracked and followed by various governmental and, increasingly, commercial tracking systems (e.g. United States Space Force’s 18th Space Control Squadron—Space Surveillance Network (SSN), U.S. Department of Commerce (National Oceanic and Atmospheric Administration (NOAA))—Traffic Coordination System for Space (TraCSS), European Union Space Surveillance and Tracking service (EU-SST). These efforts are focused on Space Situational Awareness (SSA) and Space Traffic Management (STM) to better manage objects in orbit and vehicles transiting the various space domains. These same entities track objects that are reentering the earth’s atmosphere. When an uncontrolled object is projected to demise and reenter the earth’s atmosphere various entities will begin to produce reentry predictions that are updated as the object proceeds to reentry. As shown later (see section 3), predictions are complicated and subject to uncertainty around the exact reentry location and debris pattern that will be generated by the object’s demise on reentry. Due to the many unknowns associated with uncontrolled reentries, an accurate risk assessment is currently not practical, and therefore usually no AHAs or associated NOTAMs are produced. Without the AHA and NOTAM, aviation operators and air traffic control are unable to avoid the risk associated with uncontrolled reentries as they lack important information to act appropriately.

In addition to the location and risk assessment uncertainty, there is no integrated method for communicating reentries and the risk profiles associated with the reentry. The limited information available is often presented in a format that is not understood or actionable for risk mitigation. While the large majority of the reentries do not present a significant risk, due to the location of the reentry, the ability to distinguish which reentry events present a risk and the degree of the risk is an important first step.

3. Challenges in Managing Uncontrolled Reentries

3.1. Prediction Limitations

Currently there is no unified alerting system capable of delivering real-time, actionable information to effectively and efficiently support safety measures by notifying public entities about the risks associated with uncontrolled reentries. It should be mentioned that efforts are being made to develop and provide appropriate services. For Europe, the EU-SST (EU Space Surveillance and Tracking) should be mentioned here, which is part of the Space Situational Awareness (SSA) component of the EU Space Programme. One element of the EU-SST mission, the Re-entry Analysis service "provides risk assessment of uncontrolled re-entry of man-made space objects into the Earth’s atmosphere and generates related information.“
Nevertheless, the ability to provide accurate on-time information is limited or constrained by:

A. The inability to accurately forecast a reentry location for an uncontrolled reentry: Atmospheric drag and reentry forces that control the reentry of a vehicle are unpredictable and difficult to forecast. In addition to uncertainties about atmospheric densities in high altitude layers, missing information and difficulties in prediction of the orientation and movement of the object itself pose a significant challenge to determine and calculate accurate re-entry windows. The U.S. National Oceanic and Atmospheric Administration (NOAA) provides information regarding the unpredictable effects of atmospheric drag on objects in orbit [2].

B. The inability to produce a real time hazard area associated with the debris dispersion of a reentry vehicle.

C. The lack of a comprehensive international messaging system that would promulgate hazard notification including the hazard area associated with the reentry.

Research is ongoing to better understand and forecast the effects of solar weather and reentry atmospheric drag forces [26]. Research that employs generative Artificial Intelligence (gAI) to better predict these forces effects and predict reentry location is underway [27]. For critical objects, extended tracking capabilities may help to better monitor the degrading orbit and the object orientation during the late phases of orbital decay and the actual reentry process. Research initiatives are also underway to enable the real time production of hazard areas associated with debris producing events associated with launch of space vehicles (see for example [4]). That same research can be expanded to also focus on reentry vehicles.

The need for better management of these events has been espoused and endorsed by the international aviation community and ANSPs around the globe. This need has been expressed and documented in various international forums. The Outer Space institute conducted a workshop at McGill University February 17 and 18, 2023 and produced the workshop report, “Montreal Recommendations on Aviation Safety and Uncontrolled Space Object Reentries”[3] that included recommendations for the constraints listed above. The inability to accurately respond to these events poses a risk to the aviation community. This risk is also detailed in the previously cited FAA report to the U.S. Congress “Risk Associated with Reentry Disposal of Satellites from Proposed Large Constellations in Low Earth Orbit”[1].

The FAA report to the U.S. Congress also concluded that by 2035 the debris risks associated with debris reentering from large satellite constellations in LEO include:

A. The risk to aircraft also increases by over an order of magnitude in 2035 from 1.0E-3 (1 out of 1,000 in 2021) to 8.4E-2 (84 out of 1,000)
B. The number of worldwide objects hazardous to aviation is projected to increase by 40 times the number from 2021

In response to these escalating threats, the “Montréal Recommendations on Aviation Safety and Uncontrolled Space Object Reentries” [3] advocate for international regulatory measures requiring controlled reentries, where defunct satellites and spent rocket stages are actively maneuvered to minimize risks to aviation and populated areas. Released in March 2023, these recommendations were developed by international experts. They highlight the global implications of space activities, emphasizing that the use of space by any single state can pose risks to other states. To mitigate these risks, the recommendations call on states to establish requirements to avoid uncontrolled re-entries of space objects. By emphasizing global cooperation, risk mitigation strategies, and the implementation of technical solutions—such as ensuring sufficient fuel reserves for controlled deorbiting—the recommendations serve as a crucial framework for addressing the mounting concerns associated with uncontrolled space object reentries and their implications for aviation safety.

To address the residual risks posed by uncontrolled space object reentries, the Montréal Recommendations call for” the development of standardized procedures for issuing and responding to precautionary safety warnings. These standards should build upon existing aviation coordination frameworks to ensure seamless integration into current safety protocols. They must facilitate rapid decision-making while maintaining consistency in risk assessment and response. Given the dynamic nature of uncontrolled reentry events, the standards should account for the evolving uncertainty of reentry footprint locations, particularly as reentry time approaches. Furthermore, they should prioritize operational safety, recognizing that, in some cases, inaction may be the safest response. Effective cooperation among states, especially neighboring ones, will be enhanced through the adoption of common risk criteria, reliance on widely accepted information sources, and the clear identification of responsible state authorities. These measures collectively aim to minimize the risks posed by uncontrolled reentries while promoting a coordinated international approach to aviation safety.” [3]

3.2. Operational Impact

Current methods for defining reentry risk to aircraft are limited by the lack of timely and accurate reentry location determination, incomplete or absent information on the materials and elements of the reentering object, and the orientation of the reentering object. Any risk assessment naturally has to be a conservative estimate due to these unknowns. Below is a depiction of a typical reentry risk profile extending for 2000 kilometers (km) while being rather narrow with a width of 70 km (Figure 5). Also depicted are airline traffic routes from 2021 (Figure 6). The ability to protect large risk profiles is complicated by congested airspace.

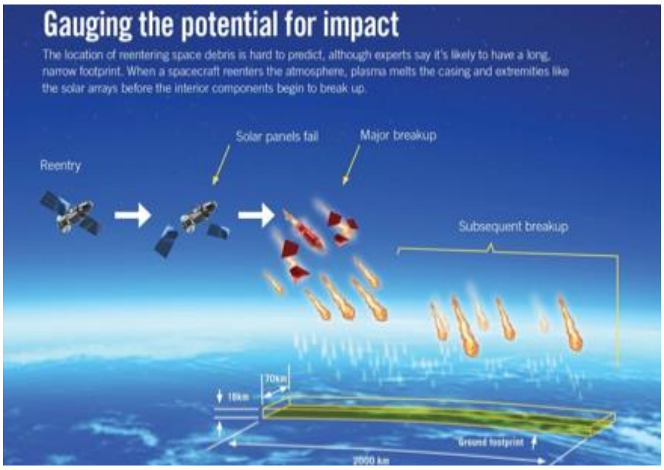


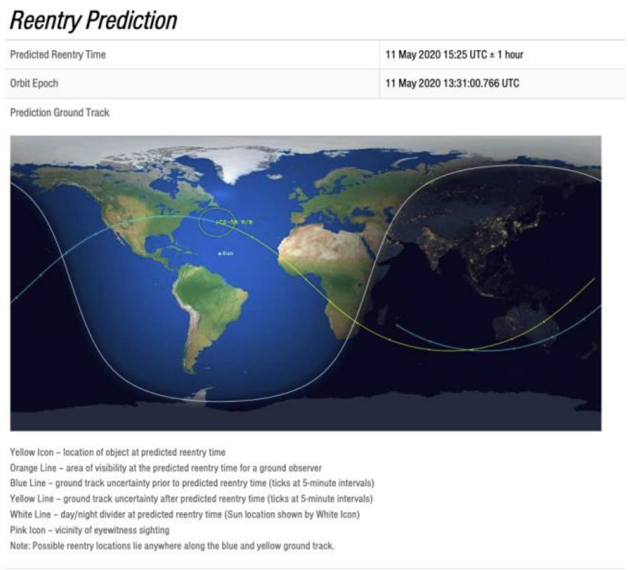
Figure 5: Schematics of a typical re-entry risk profile [1]

Figure 6: World airline traffic routes, 2021 [1]

4. Current handling of uncontrolled re-entries: The Long March 5B rocket body examples

A series of uncontrolled reentries of Chinese Long March 5B (CZ-5B) rocket bodies have occurred in the last 5 years. The maiden voyage of the CZ-5B lifted off on May 5, 2020 from the Xichang Satellite Launch Center in China. The core rocket body measuring 98 feet long,16.5 feet wide, and weighing 21 metric tons [7] subsequently reentered the earth's atmosphere on May 11, 2020 with debris reported to have landed along the Ivory Coast of West Africa. Below is the reentry prediction (Figure 7) and debris recovery information (Figure 8) collected and documented on the Aerospace Corporation's reentry tracking website [12]. Debris from this reentry was reported to have landed in an African village on Africa's Ivory Coast, depicted below (Figure 9) [8][9][10][11].

On a successive mission, China launched a CZ-5B on April 29, 2021, from the Wenchang Space Launch Center, China followed by an uncontrolled reentry of the rocket body with debris reported to have landed in the Indian Ocean on May 9, 2021 [7][11]



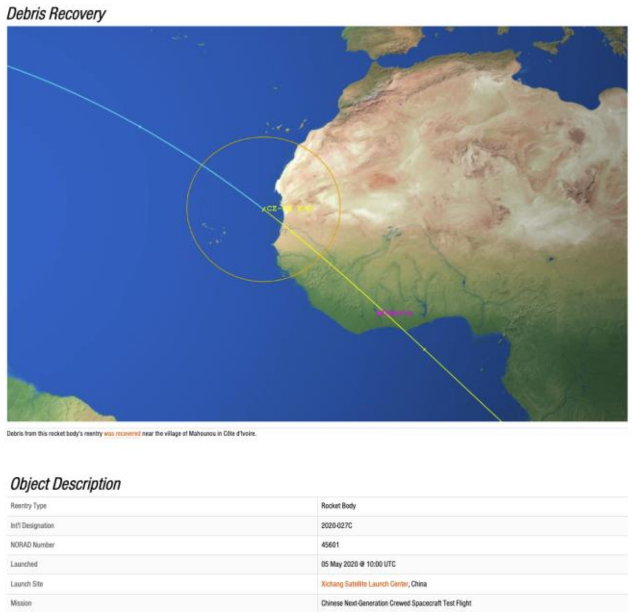
Reentry Prediction

Predicted Reentry Time	11 May 2020 15:25 UTC ± 1 hour
Orbit Epoch	11 May 2020 13:31:00.766 UTC

Prediction Ground Track

Yellow Icon – location of object at predicted reentry time
Orange Line – area of visibility at the predicted reentry time for a ground observer
Blue Line – ground track uncertainty prior to predicted reentry time (ticks at 5-minute intervals)
Yellow Line – ground track uncertainty after predicted reentry time (ticks at 5-minute intervals)
White Line – day/night divider at predicted reentry time (Sun location shown by White Icon)
Pink Icon – vicinity of eyewitness sighting
Note: Possible reentry locations lie anywhere along the blue and yellow ground track.

Figure 7: Reentry prediction for CZ-5B Rocket Body (NORAD ID 45601) [12]



Debris Recovery

Debris from this rocket body's reentry was recovered near the village of Mahounou in Côte d'Ivoire.

Object Description

Reentry Type	Rocket Body
Int'l Designation	2020-027C
NORAD Number	45601
Launched	05 May 2020 @ 10:00 UTC
Launch Site	Xichang Satellite Launch Center, China
Mission	Chinese Next-Generation Crewed Spacecraft Test Flight

Figure 8: Debris recovery location associated with CZ-5B Rocket Body (NORAD ID 45601) [12]

On October 31, 2022, China launched a CZ-5B from the Wenchang Space Launch Center, China on a similar mission profile as the two previously cited missions with the rocket body reentering the earth's atmosphere on November 4, 2022. Initially predicted to reenter over southern Europe, the event prompted the European Space Surveillance and Tracking (EU SST) organization to issue warnings. These warnings triggered the issue of a Safety Information Bulletin by EASA [14], which then had been picked up by several states and Eurocontrol, involving also the European Aviation Crisis Coordination Cell (EACCC). In response, and based on the documented debris risk from the previous mission, Spain and France temporarily closed parts of their airspace, causing delays for 645 flights, with some aircraft being diverted mid-flight [6][15], due to short lead times between the announcement of airspace closures and their implementation. Other countries under the predicted reentry path, like

Portugal, Italy, and Greece, chose not to impose restrictions but experienced increased air traffic from diverted flights.

Figure 9: Discovered debris associated with CZ-5B Rocket Body (NORAD ID 45601) [10]

The incident exposed gaps in international coordination and preparedness for such events [15]. The discussed uncertainties in predicting the eventual re-entry location and associated short lead times for updated re-entry information that can produce actionable information for ANSPs to efficiently and effectively protect affected airspace sections, were evident and contributed to the different approaches and decisions of the countries involved.

5. Proposed Approach

To effectively address the challenges outlined, a multi-faceted approach is proposed. Initially, short-term strategies for assessing and mitigating immediate risks are considered. Subsequently, solutions are introduced that focus on the rapid, real-time dissemination of critical information, supported by advanced tools to enhance accuracy and reliability. Additionally, essential communication frameworks are explored to ensure that the necessary information reaches relevant stakeholders efficiently.

5.1. Near Term Opportunities

In the near term the focus needs to be on developing and providing relevant information to ANSPs and aviation stakeholders in a timely and understandable format. Work needs to occur on the provision of the most accurate hazard area information in a timely manner. This will naturally be limited due to the unknown elements, especially of legacy or classified systems with unknown components.

As reentry prediction information is already being produced and gets updated to the best of available information, those existing services (provided e.g. by EU-SST and CSpOC) need to be exploited for use. The gaps – or ambiguities - in internationally harmonized procedures for the initiation of protective measures need to be addressed, as exposed during the CZ-5B reentry events in 2022 (see section 4). Harmonization of risk assessment methods will remain a challenge though, as they are often linked to national regulations and may differ from state to state.

5.2. Real-Time Data Provision (Enhanced object tracking and reentry prediction capabilities)

As mentioned in section 3, the inability to accurately predict the exact reentry location is a key gap to the ability to manage reentry risk. Pinning down the reentry location depends on the ability to model the effects of atmospheric forces on the object that will dictate the reentry profile. Currently, reentry predictions are modeled by a network of sensors that provide object location, altitude and trajectory. Due to shortfalls in sensor data the exact location of most uncontrolled reentering objects is unknown. Increasing sensor data and the ability to "track" vehicles of interest in real-time, along with improved modeling of atmospheric forces, will improve reentry location predictions. There are many efforts underway to provide these capabilities.

Recent advancements in space object tracking have the potential to improve reentry predictions through both ground-based and satellite-based systems. Ground-based initiatives include ESA's DRACO mission [16], which will study satellite disintegration upon reentry, and the Aeolus assisted reentry, demonstrating assisted deorbiting [17]. Projects like DeCAS [18] provide real-time impact predictions, while advanced radar facilities and networks such as the German TIRA [19] and LeoLabs global radar network enhance tracking capabilities. Satellite-based systems, such as the U.S. STSS and the forthcoming HBTSS, leverage infrared sensors for continuous tracking of high-speed objects, including reentering debris. These developments enhance situational awareness, and can support more accurate and timely risk mitigation measures.

Given the inherent limitations of ground-based tracking systems, including optical sensors and radar devices constrained to land-based locations, satellite-based solutions offer significant potential for continuous monitoring of reentering objects. This capability is particularly crucial during the final orbits preceding atmospheric reentry. While such advancements will enhance the prediction of reentry locations, precise determination of the affected area will likely only be feasible shortly before the object's breakup in the atmosphere. Consequently, equally sophisticated systems are required to process and rapidly disseminate this information to support timely air traffic safety measures.

The next step and the focus of this paper is providing the ability to leverage this data in real-time to provide ANSPs the information they require for notification and tactical management of the reentry risk.

5.3. Real-time data provision through integration of Advanced Tools

To enhance air traffic safety during planned space operations, such as rocket launches and controlled spacecraft reentries, various procedures and systems have been developed over recent decades, particularly in the United States. This advancement has been influenced by past missions and the increasing frequency of such events. Two primary objectives guide these efforts: ensuring air traffic safety and minimizing operational disruptions.

The Columbia disaster on 1 February 2003 was a pivotal event that highlighted deficiencies in existing mechanisms for timely air traffic control notifications and airspace assessments in the event of debris fallout. While no secondary collisions between debris and aircraft occurred, the incident underscored the need for improved coordination. In response, the FAA developed new procedures and tools to enhance air traffic management in such scenarios.

One key outcome of this process was the development of the Space Data Integrator (SDI) (**Fehler! Verweisquelle konnte nicht gefunden werden.**). This system aims to safeguard air traffic from the potential risks of failed space missions by leveraging real-time data processing and communication. By enabling dynamic airspace management, SDI facilitates the seamless integration of launch and reentry operations into the National Airspace System (NAS), optimizing both safety and efficiency.

Figure 10: HMI of the Space Data Integrator during a monitored launch

SDI fuses state vector data received from the launch or reentry operator in real time with risk assessment profiles, and other mission specific information and presents the information on a graphical display. The SDI sends relevant information including position and hazard area information to the FAA’s Traffic Flow Management System (TFMS) which enables the visualization of risk assessment data, near real time launch or reentry vehicle information and aircraft operating in the vicinity of the operation.

SDI facilitates the activation of Debris Response Areas (DRAs) in the event of an anomaly on launch. During recent missions, SpaceX Starship Flight 2, November 11, 2023, and SpaceX Starship Flight 7, January 16, 2025, mishaps resulted in debris propagation outside of the pre-planned AHA. DRAs were activated in real time and Air Traffic Controllers in affected facilities managed traffic in an effort to avoid potential debris fields. A key takeaway from these events was the demonstration of air traffic control (ATC) real time response to a debris generating event. Given information in real time with a robust communication system ATC can react to mitigate risk. While these were controlled launch missions many of the lessons learned can be extrapolated to a future response capability associated with uncontrolled reentries. These events occurred in surveilled areas with direct pilot-controller communication systems. DRAs and the ability to respond in real time is currently limited by ATCs ability to tactically manage traffic, in effect limiting response to areas with surveillance and direct and rapid pilot-controller communications, as cited above. Consequently, DRAs have not been expanded to oceanic areas where ATC tactical traffic management is limited. Future planned enhancements in oceanic airspace that will increase tactical traffic management will facilitate the expansion of real time response capabilities.

Historically, European rocket launches—except for suborbital missions such as sounding rockets—have primarily taken place from the Guiana Space Centre in Kourou, French Guiana, with minimal interaction with European continental air traffic. However, the emergence of micro-launchers (with payload capacities of approximately one ton) and the development or expansion of multiple European spaceports for orbital missions have highlighted the need for a structured framework to integrate these activities efficiently into air traffic operations.

A key initiative addressing this challenge is the SESAR project ECHO [20][21], which has developed the European Concept for Higher Airspace Operations. Its successor, ECHO-2, aims to implement real-time spacecraft monitoring alongside a real-time warning and information system capable of directly relaying necessary data to Air Traffic Control (ATC) units. At the core of this effort is the SpaceTracks Real-Time Mission Monitor (RMM, Figure 11), developed by the German Aerospace Center (DLR) [22]. Adapted to the needs of the European Network Manager and installed at the "Space Desk" of the Network Management Operations Centre (NMOC) at Eurocontrol in Brussels, the N-RMM is undergoing evaluation as part of SESAR ECHO-2 [23]. The system is designed to assess risks dynamically in the event of non-nominal spaceflight events, determining affected hazard zones and initiating appropriate Air Traffic Management (ATM) responses.

Figure 11: HMI of the Real Time Mission Monitor (RMM)

Depending on whether debris remains within pre-designated flight restriction areas, a pre-calculated hazard area requiring activation, or an entirely new hazard area, the system facilitates timely communication with relevant ATC centers to coordinate airspace evacuations. This approach seeks to transition from conservative, static airspace closures for rocket launches and reentries to a dynamic, real-time airspace management system, ensuring minimal disruption to aviation while maintaining safety. Given the projected increase in spaceflight activity, such adaptive solutions are essential for sustainable aerospace integration.

5.4. Adaptation for uncontrolled reentry risk mitigation

Comparing European and U.S. approaches, both emphasize the development of digital, real-time-capable systems and robust communication networks between critical stakeholders in space and air traffic operations. These infrastructures provide the foundation for rapid information dissemination regarding affected hazard areas, enabling ATC centers to respond efficiently. By embedding reentry hazard predictions within a structured information chain—integrating forecasting models, ATM systems, and air traffic flow management components—both regional and sector-specific risks can be dynamically assessed and mitigated.

A staged approach is particularly effective for handling the evolving uncertainty of uncontrolled reentries. While precise impact locations remain highly uncertain in the days and hours leading up to an event, the timing of overflights along the object's ground track can be determined with relatively high accuracy. Early identification of potentially affected flights enables preemptive airspace planning, allowing operators to adjust flight routes in advance and minimize disruptions. As more precise reentry data becomes available closer to the event, real-time facilitate the immediate transmission of hazard area coordinates, allowing ATC centers to swiftly implement necessary mitigation measures. Furthermore, these systems enable the rapid reopening of precautionarily restricted airspace once an object's reentry has been confirmed, minimizing unnecessary disruptions to air traffic. It should not be neglected that the use of such advanced technical systems must be accompanied by the development of adapted procedures. Past re-entry events have shown that there is a fundamental need for adaptation here. With the introduction of real-time capabilities, the procedures must undergo further adjustments and support the implementation of time-critical information to ensure flight safety.

By integrating predictive modeling with real-time airspace management tools, these advancements have the potential to introduce a more resilient and adaptive approach to mitigating the risks associated with uncontrolled space object reentries while preserving the efficiency of global air traffic operations.

The described approach may even get extended beyond the application for aviation safety. Expanding improved prediction of reentry risks and real-time alerting capabilities to the maritime and terrestrial domains would leverage similar principles used in aviation safety but would require adaptations to address the unique operational environments and response protocols of maritime and terrestrial users.

For maritime applications, real-time hazard area predictions could be integrated with existing navigational systems to alert vessels of potential reentry debris zones, allowing for rapid route adjustments and enhanced situational awareness. This would necessitate collaboration with international maritime safety organizations to standardize alert formats and communication protocols. For terrestrial communities, alerting systems could be integrated with public safety networks and emergency response frameworks, enabling timely notifications to at-risk populations. This approach would require the development of geo-targeted messaging systems that can accurately convey risk levels and recommended safety actions.

6. Discussion

6.1. Balancing Safety and Operational Efficiency

Global ANSPs missions include maintaining safety while achieving operational efficiency. This mission requires clear and accurate information in a timely manner. In other words, better tactically actionable information is required to maintain safety while gaining efficiency. Airspace safety associated with reentry operations is dependent on the accurate calculation of hazard areas and the timely distribution of hazard area information. The efficiency of the system is inherently tied to the real time situational awareness of the hazard area on the same systems used to manage global flows of traffic. Air Traffic Controllers are dependent on real time situational awareness tools to maintain safety and efficiency.

6.2. International Collaboration

The FAA recently began Collaborative Decision-Making efforts for space and aviation operators, as well as involved Air Traffic Control units. The collaboration was a first-time effort to work across industries to foster awareness an understanding. This collaboration led to changes in procedures and processes across the industry and led to significant efficiency gains benefiting space and aviation participants. The same framework can be extended to the international community to realize the similar benefits.

Incorporating space operations into air traffic management has demonstrated the necessity of close collaboration between space and aviation operators to ensure the safety and efficiency of air traffic. This has been particularly evident in launch operations, where coordination between these stakeholders has been essential in mitigating risks to air traffic. The same principles can be applied to the challenge of uncontrolled space object reentries, where the unpredictable nature of such events, coupled with their cross-border effects, necessitates a coordinated international response. Effective collaboration at a global level can facilitate efficient air traffic management in such situations while ensuring that safety risks are minimized.

A key demonstration of how such collaboration can be operationalized was provided by the DLR-FAA Data Exchange Project (DEP). The project illustrated how data exchange and aligned procedures can support the handling of cross-border space-related operations in airspace. The DEP demonstrations highlighted the importance of pre-mission planning and real-time mission status updates to enhance preparedness, situational awareness, and the ability to maintain a common operating picture across multiple stakeholders. Through exercises and demonstrations, the project confirmed that space operations related data could be effectively exchanged and utilized for both launch and reentry operations within air traffic management. Moreover, it reinforced the necessity of providing relevant information to all decision-making stakeholders to optimize both air and space operations.

Although the DEP project primarily focused on U.S. and European stakeholders, its findings are transferable to a broad range of missions and space-related operations involving other regions and their respective aviation authorities. This becomes particularly relevant when considering launches and reentries that affect airspaces controlled by multiple Air Navigation Service Providers (ANSPs), such as within Europe or on a global scale.

From a technical perspective, the DEP project successfully demonstrated the feasibility of utilizing the System Wide Information Management (SWIM) framework for data exchange, improving upon traditional NOTAM-based airspace notifications by enabling dynamic data sharing. However, given the time-critical and reliability requirements of spaceflight operations, the study also suggested that additional dedicated communication protocols and infrastructures might be necessary to complement SWIM-based communication. Furthermore, international harmonization of risk assessment methodologies and hazard area calculations was identified as a critical factor for interoperability, particularly in the context of licensing launch and reentry operations.

Moving forward, international agreements will be a key enabler in transferring the insights gained from the DEP project toward improving the management of uncontrolled reentries from a global perspective. Establishing internationally harmonized frameworks for data exchange, risk assessment methodologies, and hazard area calculations will be essential to ensuring interoperability and coordinated decision-making among stakeholders. The DEP results demonstrate the feasibility of integrating spaceflight data into air traffic management processes, and these insights can serve as a foundation for developing a globally coordinated approach to handling uncontrolled reentries. By building on the lessons learned from DEP, future initiatives can explore how enhanced data sharing, aligned procedures, and cooperative frameworks may contribute to mitigating risks and improving airspace safety in the face of increasing space activities.

7. Conclusion and Recommendations

The previous analysis highlights the critical role of real-time data and predictive tools in enhancing aviation safety during uncontrolled reentry events. Accurate reentry location predictions are currently hindered by limitations in modeling atmospheric forces and insufficient sensor data. Advancements in real-time tracking, improved atmospheric modeling, and ongoing research on solar weather impacts have the potential to narrow down this gap. Notably, the use of gAI shows promise in refining predictions of reentry forces and locations.

Efforts to develop digital, real-time-capable systems and robust communication networks in both Europe and the U.S. demonstrate the importance of rapid information dissemination between space and air traffic stakeholders. By integrating reentry hazard predictions within a structured information chain—including forecasting models, ATM systems, and air traffic flow management—dynamic assessment and mitigation of regional and sector-specific risks can be achieved. A staged approach looks particularly promising in managing the uncertainty of uncontrolled reentries, enabling proactive airspace planning and minimizing flight disruptions.

A key finding is the necessity of adapting operational procedures to fully leverage real-time capabilities. As time-critical information becomes more readily available, procedures must evolve to support rapid decision making and transmission of hazard area coordinates to facilitate timely mitigation measures. The importance of real-time alerting is further underscored by the ability to swiftly reopen restricted airspace once reentry events are confirmed, thereby minimizing operational disruptions

Future research and development should focus on enhancing interoperability between space and aviation systems and advancing prediction technologies. Incorporating space operations into air traffic management has underscored the importance of close collaboration between space and aviation operators to maintain air traffic safety and efficiency. This is particularly crucial for managing uncontrolled reentries, where unpredictable trajectories and cross-border impacts require coordinated international responses. To further advance aviation safety during uncontrolled reentries, international harmonization of risk assessment methodologies and hazard area calculations is essential. This will enable interoperability and coordinated decision-making among global stakeholders. Future initiatives should prioritize establishing internationally agreed-upon frameworks for data exchange and risk assessment.

By capitalizing on these developments and intensifying international cooperation, the aviation and space community can support a better anticipation and mitigation of risks associated with uncontrolled re-entries, ensuring safer and more efficient air traffic management in an era of expanding space activities.

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