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Assessing the Impact of Uncontrolled Space Object Re-entries on Air Traffic Management Operations

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With the growing number of activities in space, higher airspace, and conventional Air Traffic Management (ATM) domains, the likelihood of uncontrolled space object re-entries impacting airspace operations is increasing. Such events pose a potential safety threat to airborne traffic and challenge the efficiency of current ATM procedures. With the uncertainty of the exact time and location of a space object re-entry, and the velocities involved in orbit, it is proven difficult to have a specific and exact warning for an expected re-entry event. Recent real-world cases have shown inconsistent responses, ranging from complete airspace closures, causing significant disruptions and delays, to inaction, which may become untenable as space activity expands.

This research addresses the question: *How should ATM deal with uncontrolled re-entries from space?* The study develops a use-case scenario in which a returning space object is detected shortly before its expected entry into Dutch airspace above Amsterdam Schiphol Airport, one of Europe's busiest hubs. A traffic simulation was developed to explore possible operational responses within this limited timeframe.

Based on the simulation, a set of procedures is proposed to enable ATM to safely and efficiently manage such events. For instance, flights are categorized into *critical* and *non-critical* groups to facilitate prioritization, ensuring that aircraft most at risk or constrained by operational needs received immediate attention. In addition, the study identified the importance of providing controllers with visualization tools depicting the *predicted impact zone* and uncertainty area and time window, allowing for better situational awareness and decision-making under time pressure.

The study concludes that a structured approach combining improved space object tracking capabilities, predefined risk assessment zones, and collaborative decision-making between ATM and space operations stakeholders can significantly enhance both safety and efficiency during uncontrolled re-entry events. Recommendations are proposed for integrating these procedures into existing ATM frameworks to better prepare for the increasing interaction between the space and aviation domains.

Keywords: *ATM, STM, Re-entry, Airspace, Procedures, Safety*

1. Introduction

The frequency of re-entry events is increasing with the continued development of the space industry, with an average of 116 tons of uncontrolled debris entering the Earth's atmosphere every year between 2010 and 2022 [1]. While most of these pieces of debris burn up well before posing a danger, some of the more massive objects might pose a threat. For example, the uncontrolled re-entry of a Long March 5B launcher body in November 2022 over Southern Europe caused the closure of large parts of the Spanish, French, and Italian airspace, leading to major disruptions [2]. This incident, as well as studies that investigated the impact on European airspace to both controlled [3] and uncontrolled [4], [5] events, show that the current manner of managing air traffic lacks the necessary robustness to minimize traffic disruption.

A report conducted by the Federal Aviation Administration of the United States of America [6], based on a previous report by The Aerospace Company [7], estimates that the probability of the uncontrolled re-entry of debris to catastrophically damage an aircraft in-flight is going to be 7 in 10,000 by the year 2035. The risk might further increase in the future if both the aviation and space industry continue to develop at the current pace. This highlights the need for the development and improvement of current systems and procedures to prepare the European airspace for such events.

Previous research highlights multiple factors that are currently deficient. Kaltenhäuser et al. [8] show that the infrastructure for rapid information exchange between various supervisory authorities (e.g., space tracking and air traffic management organisations) is lacking but of high importance. Ocaya and Malevu [9] identify that current space debris trajectory prediction capabilities are limited, and show that the development of more probabilistic models and the improvement of atmospheric modelling are needed. Spinielli et al. [10] propose a method through which the complete closure of large sections of airspace is avoided. Bernelli-Zazzera et al. [11] show that the size of the impact area has a high impact on the manner in which air traffic management can be optimized for re-entry situations. Udristioiu et al. [12], as part of the European Concept for Higher Airspace Operations (ECHO) project, propose the integration of higher airspace operations through a framework based on the simulation and modelling of operational scenarios within an iterative feedback loop.

In accordance to the procedure put forward by the ECHO project, the work at hand implements an iterative simulation-based procedure development process through which an uncontrolled re-entry scenario is investigated within the high-density airspace of The Netherlands. The focus of the study is to determine air traffic management procedures that controllers would need to apply for this situation that could be extrapolated as a generalized ruleset applicable for the airspace of other countries.

The paper is structured as follows: Section 2 describes the chosen uncontrolled re-entry scenario, as well as the methodology and assumptions used to develop the simulation and traffic management procedures. Section 3 presents the results of the process, as well as insights derived from metric visualizations. The recommended set of procedures and best practices are summarized and discussed in Section 4. Lastly, recommendations for future research and developments for supporting the readiness of authorities for re-entry events for European airspace are presented in Section 5.

2. Methodology, assumptions and procedures

2.1 Use case scenario description

The approach used in the work at hand is based on the simulation of a realistic use-case scenario. The use case concerns BRIK-II, the first Dutch MoD (Ministry of Defense) satellite, developed as a technology demonstrator mission for geolocating RF sources. This satellite was a 6U platform, launched with Virgin Orbit on June 20th 2021 into a 550km altitude, 60°

inclination orbit [13]. As such, the satellite passes over The Netherlands, thus providing sufficient down-link occasions. The satellite did not have maneuvering capabilities, has performed it's intended task above expectation and is assumed to have burned up in the atmosphere during re-entry on November 12th 2025 after more than 5 years of operation. For the use case, the BRIK-II orbit data has been used and the hypothetical case that a re-entry was pending on July 1st, 2025 as the satellite crossed The Netherlands with the ground track shown. Also, typical space debris object characteristics were used to calculate the possible trajectory that such an object might take. The trajectory is based on the assumption that it would not break-up and, as such, the cross-track deviation risk does not take into account a break-up event. It was assumed that a notification of re-entry can be given approximately 17 minutes before the object would reach commercial flight altitudes. This value is based on balancing a realistic trajectory time from de-orbiting to ground, trajectory prediction accuracy, and time required by ATC to clear the airspace.

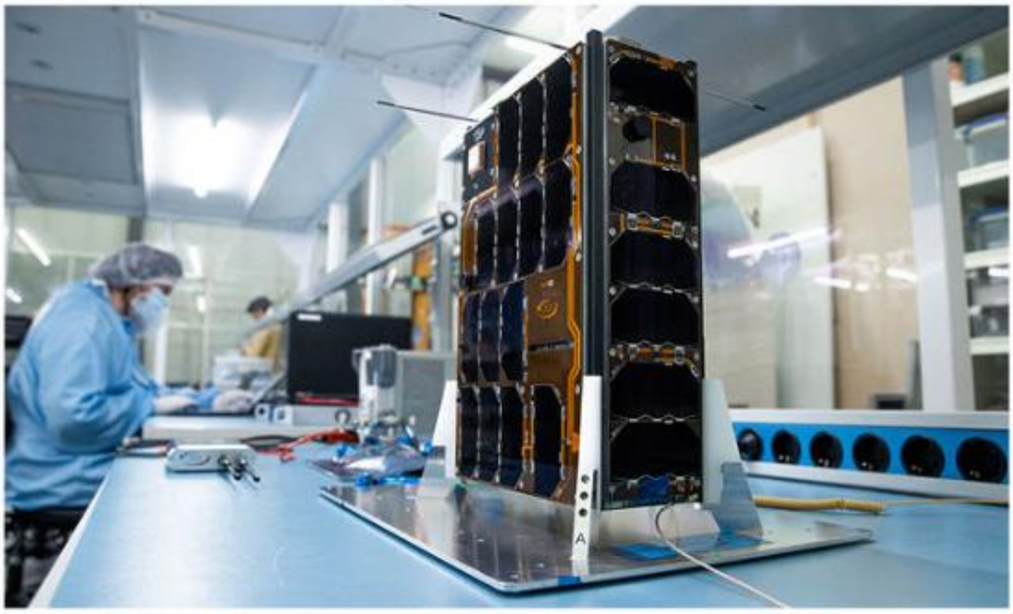

Figure 1: BRIK-II: first Dutch MoD satellite (6U) [14].

2.2. Uncontrolled re-entry of BRIK-II satellite

The approach used in this work is to examine the requirements from an Air Traffic Management (ATM) perspective. Air traffic controllers need to know the time window and the area of high-risk from which aircraft should be evacuated. By utilizing the information available of the satellite, such as orbit, shape, and mass, these can be predicted and communicated to Air Traffic Control (ATC) authorities.

The orbit of many objects is routinely tracked by space agencies, allowing for the constant update information such as ground track, inclination, and eccentricity, as shown in Figure 2. This information, combined with altitude predictions, provides an initial estimation on when a re-entry would occur. However, the prediction is susceptible to cross-track uncertainty, as variations will be induced by high-altitude winds, a possible break-up event and assumptions have to be made on the shape, mass, aerodynamic coefficients, air density and orbital and attitude state of the object. For this cross-track uncertainty, an analysis was done following the methodology described in [15] resulting in a cross-track width of 70 km, utilizing the three sigma limit statistical calculation.

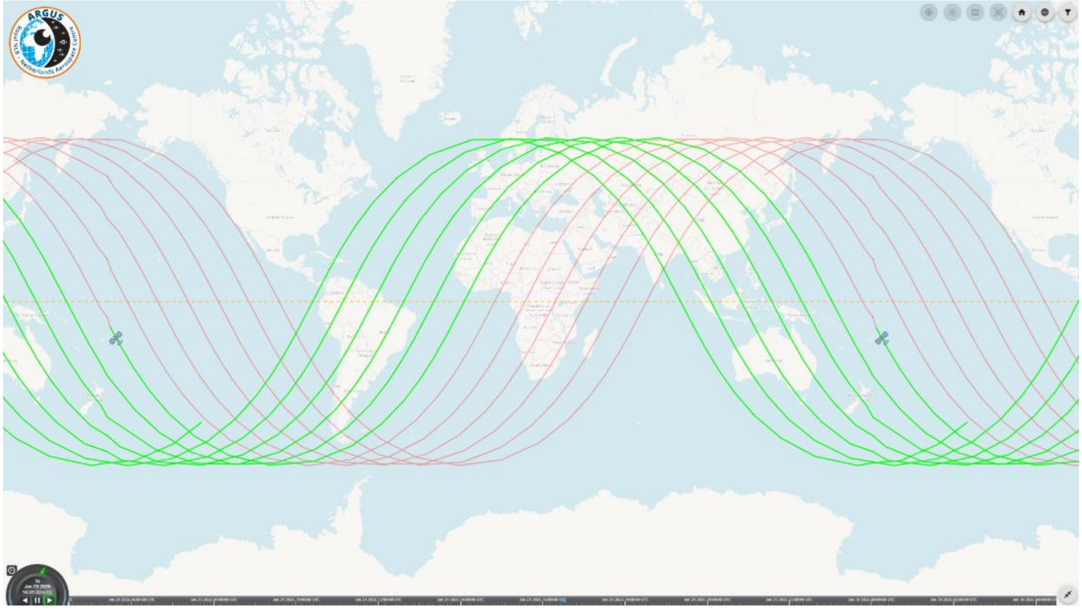

Figure 2: Ground tracks of a space object (NLR SSA-tool ARGUS – BRIK-II satellite)

The next step is to assess the information available on the re-entry trajectory. A re-entry trajectory will consist of the (horizontal) range traveled combined with the time taken for this re-entry, as shown in Figure 3. This trajectory depends on the objects' mass, area, entry angle and entry velocity. Additionally, it is assumed the re-entry is inevitable when the periapsis drops below 122 km [16], which is therefore the starting altitude of the re-entry.

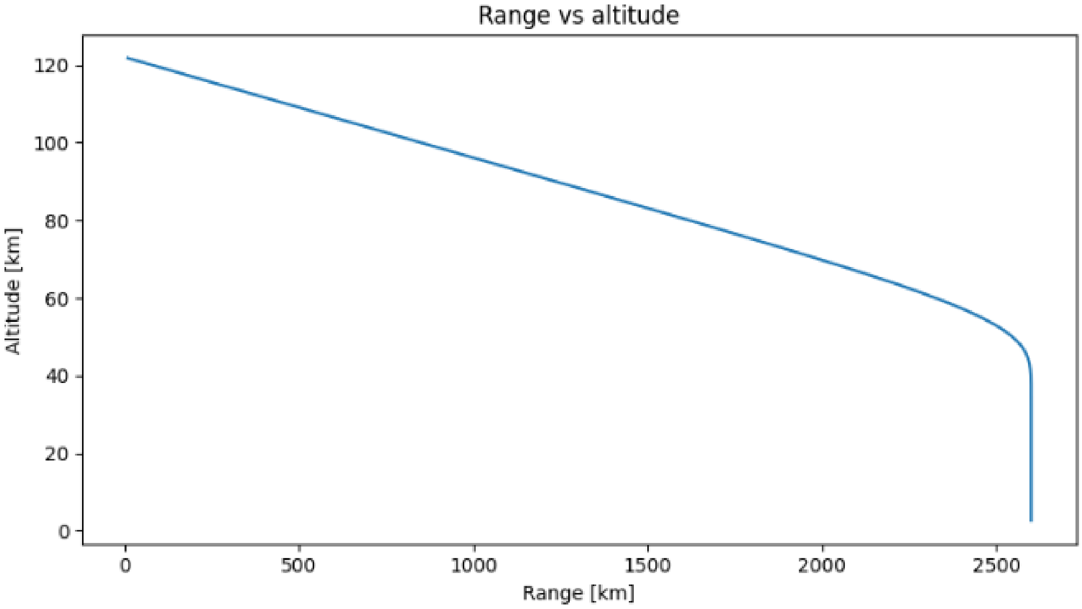

Figure 3: Example range vs altitude re-entry trajectory computed for a typical ballistic object.

Combining this with the ground track information and the boundaries of the area of interest, two hypothetical points can now be found: the "early" re-entry point, from which the last 13 km altitude of the trajectory (considered as highest flying level) to the ground will just about reach Amsterdam FIR, and a "late" re-entry point, from which the similar trajectory will almost be outside of the region. For this use-case, due to the limited size of the Dutch airspace, the early and late re-entry points coincide with the entry and exit points of the predicted trajectory within the airspace boundaries, as shown in Figure 4.

Figure 4: Predicted ground-track of BRIK-II satellite during possible re-entry event. The entry (bottom left) and exit (top right) points over the Netherlands as well as the ±35 km buffer are shown with the stars.

In this used example trajectory, the time from orbit down to an altitude of 13 km would be approximately 7 minutes, and the time it takes to vertically pass through this area to the ground takes approximately 4 minutes. We assume that the notification of re-entry is communicated 6 minutes before the object reaches the 122 km threshold, adding up to a total of 17 minutes ahead of incursion time.

This means that for ATM to perform the tasks as required in a timely manner, the space information for the use case as chosen is the following:

- Notification: Warning, re-entry pending (in the use case 17 minutes before area incursion).
- Area to be closed: ground track of the specific object across the ATM area, with a defined cross track (in the use case 70 km).
- Time of first possible infringement (i.e., airspace should be cleared at this time).
- Time of last possible infringement (i.e., airspace can be re-opened from this time).

2.3. Description of Dutch airspace operations

The Netherlands' airspace is organized within the Amsterdam Flight Information Region (FIR), which extends from ground/sea level to unlimited altitude. The airspace is divided vertically at Flight Level 245. Below FL245, Air Traffic Control the Netherlands (LVNL) controls civilian air traffic, while the upper airspace (FL245 to FL660) is under the jurisdiction of Eurocontrol's Maastricht Upper Area Control Centre (MUAC). Besides MUAC and LVNL, The Dutch military also controls certain sectors under FL195 [17].

Aircraft operating in the Amsterdam FIR fly under either Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). VFR flights navigate primarily by visual reference to the ground and must fly under VMC (Visual Meteorological Conditions). IFR flights navigate using instruments and follow air traffic control clearances.

In controlled airspace, clearance is required to enter and be under ATC service. In uncontrolled airspace, clearance is not required to enter the airspace, and the pilot does not receive services from ATC such as ensuring separation minima. That is the pilot's responsibility. Nonetheless, information service is provided, for instance being informed about traffic around the aircraft or restricted areas nearby. For uncontrolled VFR flights, ATC can only give general directions. For example, ATC can ask the pilot to leave the sector to the east, but not require a certain heading [18].

Holding patterns are oval-shaped waiting patterns used to delay aircraft when immediate approach clearance cannot be granted due to traffic congestion, weather conditions, or other constraints. Multiple aircraft can be stacked vertically within the same holding pattern by assigning different flight levels, typically separated by 1000 ft intervals. The Amsterdam FIR contains four holding points managed by Amsterdam ACC: RIVER, SUGOL, NARSO, and ARTIP as seen in Figure 5. These holds are for arriving traffic to Schiphol airport in Amsterdam.

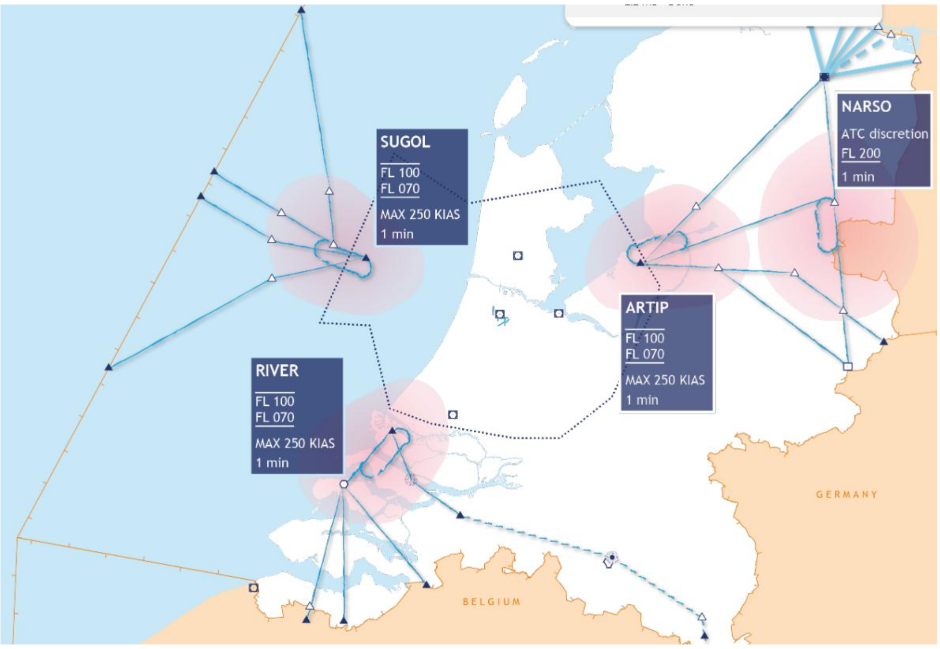

Figure 5: Holding patterns typically used by air traffic controllers in Dutch airspace [19].

2.4. Simulation-based iterative approach

An iterative approach was used to converge on a set of procedures that would enable the management of air traffic towards a safe situation in the case-study at hand. First, historical flight data was obtained for the 1st of July 2025 between 14:00 and 15:00, matching the predicted re-entry moment of the BRIK-II satellite. This data was used to create a simulation scenario for the BlueSky ATC simulator [20], as shown in Figure 6.

Using BlueSky, the actions implemented after issuing the re-entry warning were iterated upon by incrementally modifying the instructions given to aircraft until a desirable outcome was reached. Furthermore, the use of the simulation allowed for the output of relevant metrics as well as the creation of alternative scenarios used for comparison: a baseline scenario, which simulates the data without any modification to operations, or an airspace closure scenario, where new aircraft are not allowed to enter the danger area, but aircraft within the area allowed to continue cruising.

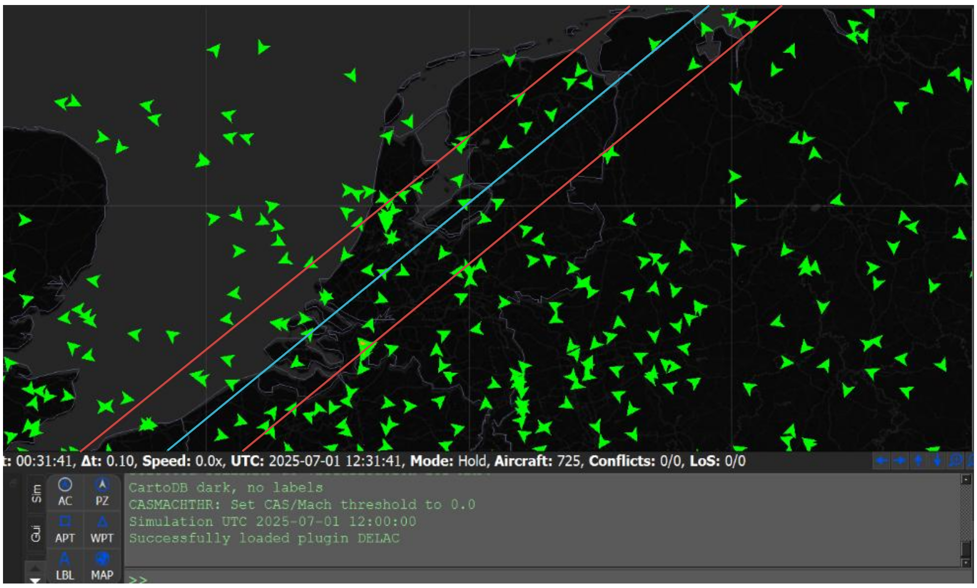

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Figure 6: Simulation of use-case scenario within BlueSky, with danger zone highlighted on the map.

3. Results

There are two sets of resulting procedure recommendations. The first set is on the operational procedures that should take place once a notification of a re-entry is received by ATC. The second set is for longer term preparation for such events.

3.1 Recommended operational procedures

1. Manage traffic flow:
Immediately upon notification of the possible re-entry event crossing into the controlled airspace, stop accepting traffic from adjacent sectors and suspend all departures from airports within the affected region. This prevents additional aircraft from entering the airspace volume that may require intervention.

2. Affected aircraft identification:
Identify which aircraft require intervention by determining their predicted position relative to the danger zone during the re-entry time window. This can be accomplished through trajectory vectoring for individual aircraft. However, operational efficiency can be improved by utilizing visualization tools that project aircraft positions forward to the danger time window. Such tools, currently implemented at some facilities including MUAC (Maastricht Upper Area Control Centre), provide controllers with a quick overview of all affected aircraft simultaneously.

3. Select intervention strategy:
For each affected aircraft, select an appropriate mitigation action from the following options:
A. Expedite landing at the destination airport prior to the danger window.
B. Increase speed (if necessary) and transit through the danger zone before the time window.
C. Establish ad-hoc holding areas outside the danger zone.
D. Issue heading instructions to route aircraft around the zone (e.g. parallel routing with course resumption after window closure).
E. Take no action for aircraft assessed as unaffected. These are aircraft expected to be clear of the danger zone during the danger window without any intervention.
F. Divert and land at alternative airports. Aircraft with insufficient fuel reserves for holding operations must be diverted to alternate airports outside the affected region.

4. Communicate with priorities:
Execute controller-pilot communications with explicit acknowledgment requirements. Beware that two-way confirmation protocols substantially increase communication time compared to

broadcast advisories, necessitating sequential handling of aircraft. Priority must therefore be given to affected aircraft in temporal proximity to the danger zone.

5. Consider VFR traffic limitations:
Account for VFR traffic operating in uncontrolled airspace, which may not be monitoring ATC frequencies and therefore cannot receive re-entry advisories through standard communication channels.

6. Establish temporary holding areas:
When published holding patterns are unsuitable or lack sufficient capacity, establish tactical holding points at strategic locations outside the danger zone. Selection criteria should prioritize geographic separation from the re-entry zone and compatibility with subsequent traffic flow resumption.

7. Allocate arriving aircraft to holding levels:
Recognize that holding areas have limited available flight levels. Prioritize assignment of holding slots to aircraft with destinations within the danger zone, as these flights cannot resume normal operations until after the time window closes. Aircraft transiting through the affected region can alternatively be managed through heading vectors and rerouting, preserving holding capacity for flights with no planning alternative.

3.2 Preparedness recommendations

Successful implementation of the proposed procedures within the limited time available between re-entry notification and event occurrence requires longer term preparations to be in place. The following preparations are recommended.

1. Controller Training and Standardization:
Air traffic controllers (ATCOs) must receive dedicated training on re-entry event procedures prior to actual events. Standardized response protocols must be established and practiced to eliminate decision-making delays during time-critical operations. The short timeline between notification and re-entry does not allow for procedure development during the operational response.

2. Traffic Flow Protocols:
Sector management policies must establish that from the moment of re-entry notification, departures are suspended and traffic acceptance from adjacent sectors is halted. These measures are essential to reduce controller workload and limit the number of aircraft requiring intervention.

3. Human-Machine Interface Development:
Specialized visualization tools must be implemented to support ATCO situational awareness and decision-making. These systems should provide graphical representation of the danger zone including a safety margin, and projected aircraft trajectories to help in identifying affected aircraft that must be prioritized.

4. Danger Zone Definition Standards:
Space agencies and tracking entities must provide re-entry notifications that include defined safety margins on either side of the predicted ground track. The exchange of this information and its integration into ATC tools should be developed where it is lacking.

5. Military Airspace Coordination:
Use of military-controlled airspace may be necessary to implement tactical reroutes or holding patterns. Military authorities must be incorporated into re-entry notification chains and prepared to expedite airspace release procedures. Operational coordination mechanisms, such as the continuous supervisor-to-supervisor contact maintained between civil and military operations in

the Netherlands, should be established in all regions where military airspace may be required for re-entry response.

6. Space information: Re-entry specifics
It is important to have information on which objects will burn-up, might burn-up, will not burn-up (completely) to limit the number of possible re-entries impacting ATM. Additionally, details on the possible re-entry trajectories and time-to-ground need to be further investigated and variations coming from the different object specifics.

3.3 Effect of applied procedures on simulated scenario

The effect of the measures enacted on air traffic management can be seen in Figure 7. Starting from the notification time, there is a steep decline in the number of aircraft found within the 35 km buffer zone of the predicted ground track of the space object. The rate at which this area is vacated is highly dependent on its width and the number of aircraft that still need to exit it or perform an emergency landing. The simulation shows that the measures taken within this case-study were successful in vacating most of the aircraft within 20 minutes. A few unresponsive aircraft remained within the danger area, as it was deemed that some aircraft would not be able to communicate with ATC, or would be unable to vacate the area on time (e.g., gliders). Then, after normal operations were resumed, traffic reached baseline levels within approximately 30 minutes.

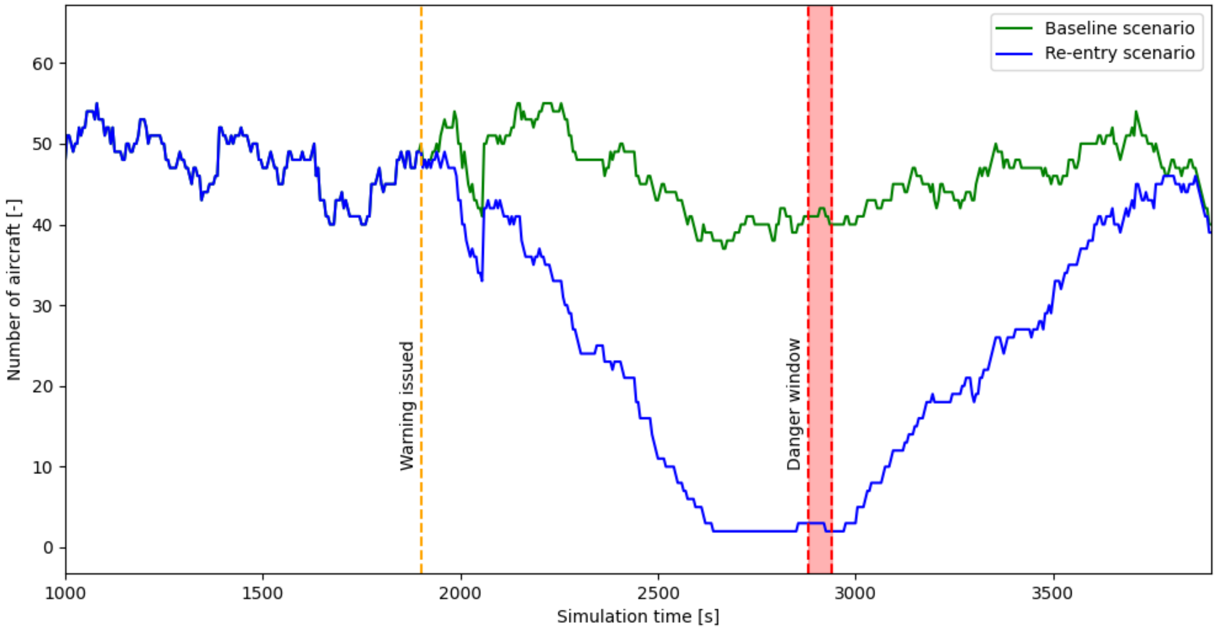

Figure 7: Number of airborne aircraft within the danger zone in function of simulation time for the baseline scenario and the re-entry emergency scenario.

The need for active traffic handling is highlighted in Figure 8, which compares the simulated re-entry scenario with the situation in which the airspace 35 km around the predicted ground track is closed for new traffic, but current traffic is allowed to continue flying unaltered. The latter strategy results in more than 20 aircraft still remaining within the danger area, showing that identifying the aircraft that require immediate intervention is critical for achieving an acceptable level of safety.

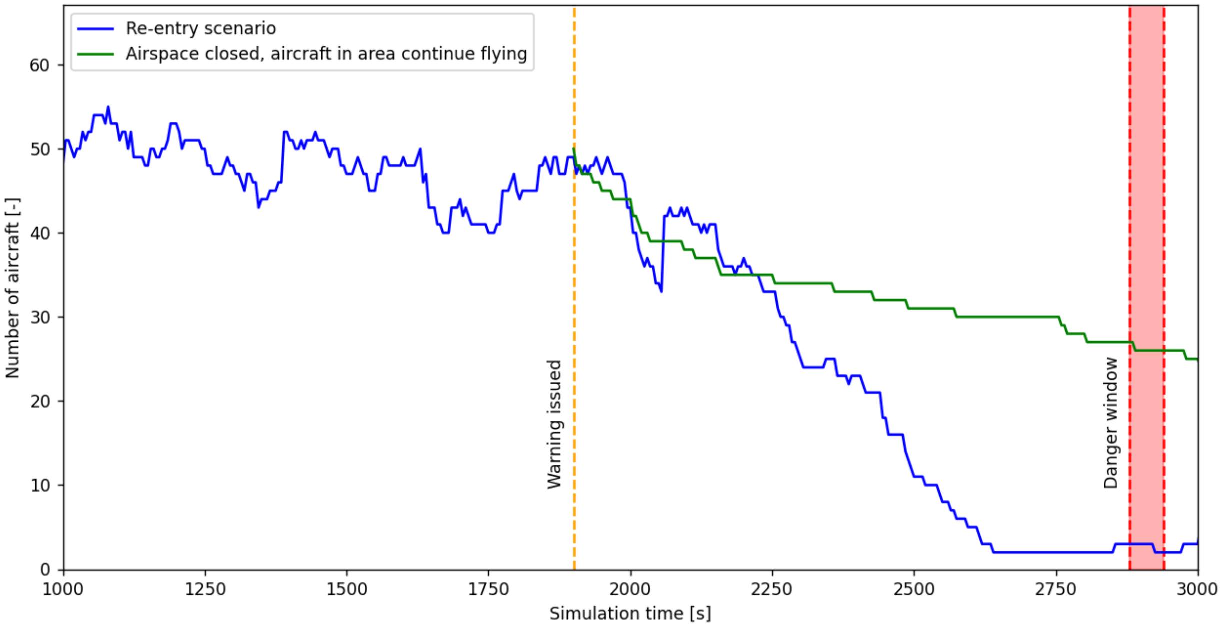

Figure 8: Number of airborne aircraft within the danger zone in function of simulation time for the re-entry scenario and the airspace closure scenario.

Lastly, one of the most important factors that influence the success of the outlined re-entry scenario is the certainty with which the danger zone can be established. While evacuating aircraft from within a buffer of 35 km of the predicted ground track was shown to be possible within the ideal conditions of the simulation, a lower buffer that maintains the same confidence level would improve the chances of such a scenario being achievable in reality as well.

Figure 9 portrays the number of aircraft that would require commands (i.e., aircraft that would otherwise find themselves within the buffer during the danger time window) in function of the width of the buffer. As the number of air traffic controllers managing traffic per sector at one time is low, a wide area that needs to be evacuated could easily overwhelm them. For example, increasing the danger zone width from 70 km (used in the use-case at hand) to 100 km can increase the number of aircraft requiring intervention from 100 to approximately 150. As these aircraft also interact with each other and separation needs to be maintained, the workload of air traffic controllers could increase beyond this proportion with increasing traffic complexity in function of sector and flow geometries at the time of the re-entry event.

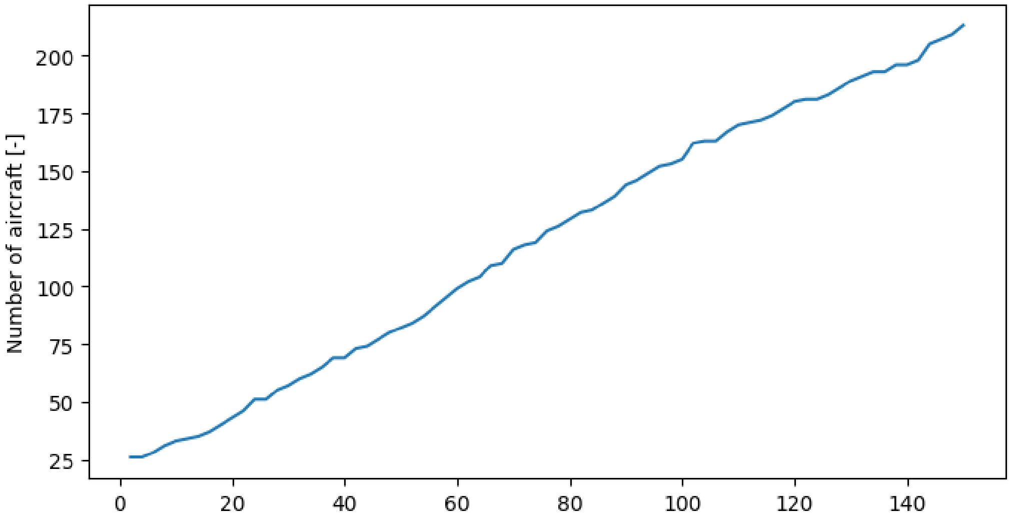

Figure 9: Number of aircraft that would require diversion commands in function of danger zone width.

4. Discussion and conclusions

This study sought to simulate air traffic management procedures in case of a predicted uncontrolled re-entry of a satellite above the airspace of The Netherlands. Using the predicted trajectory and uncertainty, a danger area and time-window was established. Then, procedures were iterated upon and applied to a realistic air traffic scenario.

Results show that, given the assumed buffer and warning time, air traffic could successfully be evacuated from the danger area. Initial actions included stopping all departures from the airport in the danger area, and halting acceptance of flights entering from adjacent FIRs. In most situations within the FIR, aircraft were either allowed to continue cruising, re-routed to avoid the danger area, directed to land at their origin (e.g., for general aviation) or destination airports, or placed into holding patterns outside of the danger zone. After the danger window passed, aircraft were allowed to resume navigation, and the airspace rapidly recovered to nominal traffic levels. The set of procedures lead to a minimization of the duration of the airspace closure.

The current study has some limitations that define opportunities for future analysis. First, the procedures were developed assuming a single uncontrolled re-entry scenario with relatively high trajectory prediction accuracy. Other scenarios can present greater uncertainty in both time and space dimensions. The danger zone definition and controller response timeline must be reassessed for a range of re-entry time windows, rather than the one use-case used in this work.

Furthermore, the use case scenario used in this work itself contains several assumptions when it comes to the expected trajectory and timing of the object re-entry through airspace. For example it is assumed that after a minute, the object has passed Dutch airspace and it is known to be safe again to resume normal operations, while in reality it may take several minutes longer if the object actually falls through to the ground. Improving this accuracy for all scenarios to be tested would improve the insights on procedures and ATCO behaviour.

Next, the proposed procedures have not been validated through real-time human-in-the-loop simulations. Controller workload estimation, stress response under compressed decision timelines, and human factors associated with low-probability high-consequence events remain unquantified. Future research involving real-time human-in-the-loop simulations can identify further procedural bottlenecks, and assess the effectiveness of decision support tools under operationally realistic conditions.

This is to also include information from the re-entry event and it’s timeliness, as having more certainty well in advance would allow for including the conflict in flight planning already. On the other end: confirmation of a sighting, possible with more ground sensors focussing on the object and sharing the information, would provide more certainty and more clearly limit the area and time of conflict. This would allow ATC to close and re-open the subsequent airspace with more confidence, for shorter time windows or not at all.

Finally, the visualization and decision support tools referenced in this study require systematic evaluation. While the capacity to "forward" traffic positions to the danger time window has been identified as operationally valuable, the optimal presentation format, information density, integration with existing controller working positions, and coordination between different sectors within the Amsterdam FIR, have not been determined. Future work should include human-machine interface design studies to develop and validate controller tools specifically optimized for re-entry event management.

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