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Space Debris and its Implications for Aviation Safety

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SUMMARY

This paper examines the implications of space debris for global aviation safety, with particular emphasis on air traffic management (ATM) operations during uncontrolled atmospheric re-entries. While the probability of direct aircraft–debris collision remains low, such events necessitate precautionary airspace restrictions that disrupt flight operations and generate significant operational and economic consequences. The paper identifies limitations in current ATM practices and space governance frameworks, as well as outlining emerging technical and procedural approaches such as dynamic airspace allocation and predictive hazard modelling to mitigate cross-domain risks and enhance operational resilience.

1. INTRODUCTION

1.1. Space activities have significantly advanced scientific knowledge, global communication, and connectivity; however, they have also given rise to the growing challenge of space debris. Commonly referred to as space junk, space debris comprises non-operational human-made objects in Earth orbit, including defunct satellites, spent rocket stages, and fragments generated by collisions or disintegration events.

1.2. Although foundational legal instruments such as the 1967 Outer Space Treaty, the 1972 Liability Convention, and the 1975 Registration Convention establish general principles of responsibility, liability, and jurisdiction in outer space (Hakeem, 2017), they provide limited guidance on the regulation and mitigation of space debris. Provisions such as Article IX of the Outer Space Treaty rely on broadly worded and non-binding obligations. At the same time, the fault-based liability regime under the Liability Convention is ill-suited to address debris-related incidents. Consequently, existing space law frameworks fall short in managing the increasing congestion of the orbital environment, underscoring the inadequacy of current space traffic management (STM) mechanisms (Ailor, 2006).

1.3. From an ATM perspective, the rapid growth of space activities has heightened concerns over uncontrolled objects re-entering Earth’s atmosphere. While most debris disintegrates during re-entry, larger components may survive, posing risks to aircraft, ground infrastructure, and populations along re-entry corridors. Recent re-entry events and launch failures have required the pre-emptive closure of extensive airspace volumes, disrupting hundreds of flights and creating cascading operational and economic impacts.

1.4. This paper examines the nature of space debris re-entry hazards, assesses their operational impact on ATM, and discusses technical, procedural, and regulatory measures that may reduce disruption while maintaining aviation safety.

2. DISCUSSION

2.1. SPACE DEBRIS AND ATMOSPHERIC RE-ENTRY CHARACTERISTICS

2.1.1. Low Earth Orbit (LEO) has become increasingly congested with debris originating from defunct satellites, spent rocket bodies, and fragmentation events (Bongers & Torres, 2024). As of 2024, the European Space Agency (ESA) estimates that more than 45,300 debris objects larger than 10 cm, approximately one million fragments between 1 and 10 cm, and over 130 million objects smaller than 1 cm are currently in orbit (ESA, 2024). While many of these objects are too small to be tracked, they are nonetheless capable of damaging spacecraft and surviving partial re-entry.

2.1.2. Uncontrolled atmospheric re-entries exhibit highly variable trajectories influenced by atmospheric density, solar activity, object mass, shape, and ballistic coefficient. These uncertainties result in large predicted impact corridors that may span hundreds or thousands of kilometres. Although the likelihood of debris intersecting an aircraft trajectory remains extremely remote, the severity of potential consequences necessitates the application of conservative risk management measures.

2.1.3. Historical events illustrate these challenges. The uncontrolled re-entry of the Long March 5B rocket body on 4 November 2022 prompted precautionary airspace closures across parts of Spain and France, affecting more than 300 flights and causing network-wide delays, despite the object ultimately disintegrating over the Pacific Ocean (Luftraum über Spanien Zeitweise Gesperrt. aero.de, 2022).

2.2. RISK ASSESSMENT FOR AVIATION OPERATIONS

2.2.1. Uncontrolled re-entries present a low-probability, high-consequence hazard to aviation. Larger debris fragments, particularly from rocket bodies and satellites, have a higher likelihood of surviving re-entry and reaching aircraft operating at cruising altitudes. Studies indicate that debris fragments weighing only a few grams can damage windscreens or engines, while larger fragments may cause catastrophic structural damage (Range Commanders Council, 2000; 2020).

2.2.2. As of mid-2024, more than 2,300 large rocket bodies remain in orbit and are expected to re-enter Earth's atmosphere in the future (Celestrak, 2024). The cumulative growth of such objects increases the frequency of re-entry events requiring ATM intervention. There is uncertainty as to whether the risk of harm arising from a collision between space debris and an aircraft complies with the internationally recognized Target Level of Safety (TLS) of 1×10^{-9} fatalities per flight hour, and preliminary assessments indicate that further quantitative analysis is required to determine alignment with established aviation safety benchmarks. Work is currently underway within relevant international fora, including the International Civil Aviation Organization (ICAO), through the ICAO Separation and Airspace Safety Panel (SASP), to examine the associated operational and safety implications and to develop appropriate risk assessment methodologies and mitigation strategies to ensure that any identified risks are managed to achieve and maintain an acceptable level of safety consistent with ICAO safety objectives.

2.2.3. Recent SpaceX Starship launch failures in January and March 2025 led to the activation of FAA debris response areas[1], resulting in nearly 500 flight delays, diversions, and airborne holds across Florida and the Caribbean, with estimated costs to operators in the millions of dollars (Lingle, 2025). These incidents highlight the increasing operational burden placed on ATM systems by the expansion of space activity.

2.3. OPERATIONAL IMPACT ON AIR TRAFFIC MANAGEMENT

2.3.1. Current ATM systems do not currently incorporate dedicated, integrated capabilities for real-time monitoring and management of space debris hazards. Coordination between civil aviation authorities, space agencies, and military stakeholders remains largely ad hoc and reactive. The absence of standardized procedures for managing uncontrolled re-entries complicates airspace planning, increases controller workload, and introduces inefficiencies into air traffic operations.

2.3.2. Predicting re-entry timing and impact locations remains inherently uncertain due to atmospheric variability and object-specific characteristics (Schmidt & Gamper, 2020). As a result, ATM responses typically rely on static airspace closures based on worst-case projections. While these measures prioritize safety, they often encompass areas far larger than the actual hazard footprint, resulting in unnecessary operational disruptions.

2.3.3. Reactive tactical measures, such as real-time rerouting, offer improved flexibility but are constrained by surveillance limitations and the difficulty of

[1] FAA Debris Response Areas (DRAs) are temporary, emergency airspace closures activated during space launch anomalies or mishaps to protect aircraft from falling debris.

rapidly evacuating airspace. Effective implementation depends on advanced tracking capabilities, automated decision-support tools, and robust cross-domain information sharing.

2.4. PROPOSED PROCEDURAL AND TECHNICAL APPROACHES

2.4.1. Several international organisations have established principles for mitigating space debris, aimed at preventing on-orbit fragmentation, removing end-of-life spacecraft, and limiting debris released during normal operations (Mejía-Kaiser, 2020). From an ATM perspective, emerging concepts seek to complement these efforts by improving airspace management during re-entry events.

2.4.2. Dynamic airspace allocation represents a potential alternative to static closures. Under this approach, temporary restricted areas are adjusted in near real-time to follow the predicted debris trajectory, reducing the geographic and temporal scope of airspace restrictions (Stefanescu et al., 2024). The FAA's NextGen framework, including concepts such as Space Transition Corridors and four-dimensional trajectory deconfliction, illustrates how predictive modelling and automation could support just-in-time airspace protection (FAA, 2020).

2.4.3. Statistical uncertainty propagation techniques can generate confidence-based hazard envelopes at relevant flight levels, enabling proportional risk mitigation (Kaltenhaeuser et al., 2017). Look-ahead prediction concepts, such as NAS (National Airspace System) Automation Boundary Entry Time, further support systematic and timely clearance of affected airspace volumes. Algorithmic routing and conflict-resolution tools may mitigate secondary conflicts arising from large-scale rerouting (Tüllmann et al., 2025).

2.5. POLICY AND REGULATORY CONSIDERATIONS

2.5.1. Despite increasing operational impacts, international legal frameworks governing STM remain fragmented and largely non-binding. Existing treaties do not mandate pre-launch notification standards, debris mitigation obligations, or data-sharing requirements for space situational awareness. Sovereignty concerns and national security considerations further limit transparency and cooperation.

2.5.2. Liability mechanisms under the Liability Convention are difficult to apply in practice, particularly when debris is unregistered or attribution is unclear. In the absence of harmonized rules, regulatory avoidance and jurisdictional fragmentation risk undermining responsible behaviour, particularly in the commercial space sector (Hitchens, 2019).

2.5.3. Addressing these challenges requires the development of a coordinated international STM framework with clearly defined responsibilities, standardized technical requirements, enforceable data-sharing obligations, and effective dispute resolution mechanisms. Institutional models established by ICAO and the International Maritime Organization may offer useful precedents for cross-domain governance (Antoni *et al.*, 2020).

3. CONCLUSION

3.1. In accordance with the proposed outcome goals of this working paper, the analysis presented supports a structured understanding of the safety implications of space debris for ATM operations highlighting areas where procedural evolution may enhance resilience and operational continuity.

3.2. The increasing prevalence of space debris and uncontrolled atmospheric re-entries represents an emerging cross-domain consideration for aviation safety and ATM efficiency. While the probability of a direct aircraft impact remains extremely low, the operational consequences of precautionary airspace closures are significant and likely to intensify as space activity expands. Current ATM responses, characterised by static and conservative measures, highlight an existing gap in the management of space-aviation interface risks.

3.3. Ensuring the continued safety and efficiency of global air traffic will benefit from a progressive transition toward dynamic, data-driven airspace management supported by enhanced surveillance, predictive modelling, and cross-sector coordination. Equally important is the establishment of a coherent international STM governance framework that balances national sovereignty with collective safety and operational resilience.

4. RECOMMENDATION

4.1. It is recommended that this working paper be accepted as information material.

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