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ATM strategies for, and impacts of, space launches

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Abstract.
There is a rapid growth of national space launch ambitions and capabilities, e.g. delivering satellites into low-earth and sun-synchronous orbits. With vertical and horizontal delivery methods, and numerous locations under consideration in several continents, the industry has faced early challenges, such as failed launches and licencing timescales. This paper explores the increasing intersection between aviation and air traffic management (ATM) with higher airspace operations (HAOs). It introduces the background and principles of space launches, before addressing the particular impacts on aviation and ATM. The strategic challenges of planning launch windows to align both with orbiting asset congestion and ATM demands, plus promulgating such information to airspace users, is discussed. In the tactical phase, the consequences of impacts on airspace users (such as the re-routing of flights) and on air navigation service providers (such as the demands of coordinating airspace closures in the context of considerable re-entry/splashdown uncertainty) are discussed. A key contribution we make in this paper is the first aircraft-specific, fuel and operating cost analysis of HAO impacts, and the first such European cost assessment, with basic impact geometries. We also propose improved aircraft-specific impact models, which include passenger-centric costs.

1. Introduction

Global economies are heavily reliant on access to services delivered from assets in space; some are obvious, such as GPS signals for transport use or military and security services, but others are less obvious. Agriculture sectors use GPS to ensure efficient farming, with over 300 000 GPS receivers already employed in the USA over a decade ago [1], equivalent to \$3.75 million (2.91€ million) per day of economic value generated. Similarly, the loss of a GPS time/date signal impacts normal life from routine financial transactions to the loss of mobile phone systems. Disruption of space capabilities can happen for various reasons, from natural factors (asteroid collision and equipment failure) to external interference. This risk to resilience led to NATO in December 2019 declaring space as the '5th Domain of Operations' [2].

The definition of 'space' continues to challenge the international community, and so identifying where the boundary between 'airspace' and 'space' remains unclear as the development of civilian high-altitude aircraft and system grows and with it the need for a degree of deconfliction at altitudes that were historically the domain of military activities. Equally, the community is lacking an international definition of 'space traffic management' (STM) in the absence of internationally agreed rules on how space traffic is deconflicted. Once in orbit, and whilst remaining there, STM is outside the scope of the paper. Nevertheless, the Kármán line, at an altitude of 100 km, is generally accepted as the boundary between airspace and space. The upper limit for civil air traffic and most military aviation is 18 km (a few unmanned aerial vehicles reach altitudes of 20 km), and the lowest practical orbit for satellites is at an altitude of about 160 km (see Figure 1 for operational altitudes for different vehicle types). A part of the area between these boundaries, from 20 to 100 km, is labelled as the 'near space'. Conventionally, this whole area has been unused and under explored, primarily utilised by transiting orbital rockets and, sporadically, for scientific purposes by suborbital and trans-atmospheric rockets. This 'near space' is becoming more used as the lower Earth orbits (LEOs) become more congested with larger constellations [3] such as CubeSat and has generated the growth of high altitude air platforms (HAPS), ranging from balloons, stratospheric satellites, high flying drones etc., all capable of significant endurance that can either transit significant distances or loiter in a location for a long time. Some are for commercial purposes (e.g., Airbus Zephyr) whilst others are for potentially nefarious or military purposes (e.g., 'spy' balloons).

The SESAR JU and EUROCONTROL define "higher airspace operations" (HAO) as "operations carried out by various types of vehicle systems that operate within or transit through the upper layers of the atmosphere"[4], which includes: supersonic and hypersonic flights; 'A-to-A' and 'A-to-B' suborbital flights, and; vehicle systems that transit through and interface with the airspace, such as orbital operations for access to space (e.g., air-launching operations into orbit) and re-entry operations from space. Higher airspace is defined as airspace "typically above altitudes where the majority of air services are provided today" and further qualified as "typically above FL550", with a later reference to "airspace approximately 60,000 ft"[1]. The focus of the analysis in this paper is the impact of HAO on conventional air traffic, through ATM measures.

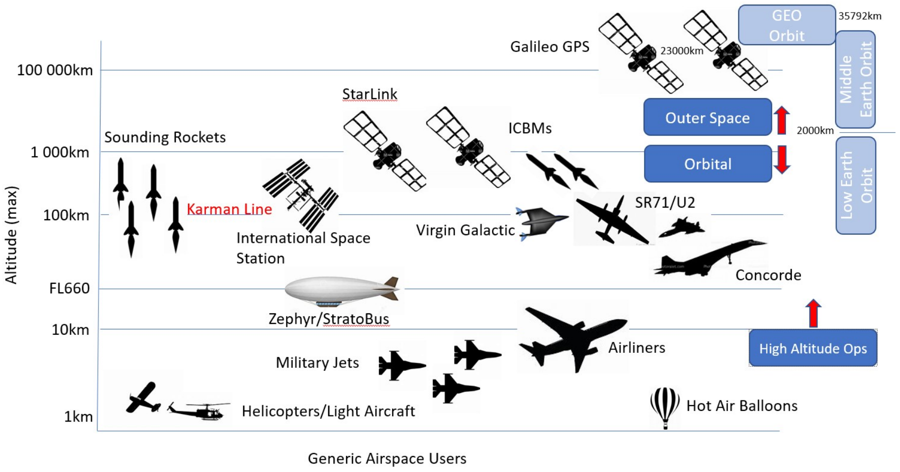

Figure 1: Airspace users at increasing altitudes.

With an increasing reliance on space-based capabilities, an ability for a country to have its own launch capability means they can deliver their own satellites without relying on other states. The complexity of accessing any orbits results in the launch time being dictated by, not necessarily by the minimum disruption to air traffic flow, but by the time window where the launcher and satellite are able to route through the congested orbits. This may mean launches need to be performed when the air traffic environment is busy.

2. Background: why space is important

Assured access to space is essential for global economies, be that for communication systems or GPS. The loss of GPS can impact all sectors, from financial services, traffic management

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[1] https://www.sesarju.eu/projects/ECHO2

to mobile phones and even accessing fuel from gas stations and using cash points. The UK's Department for Business, Energy and Industrial Strategy suggests that the global space economy will grow from £270 Billion in 2019 to over £490 billion by 2030 [5]. The terrestrial demand on space based services is growing and as such assured access to space.

2.1. Why the space – ATM interface is important

As the demand for space-based capabilities increases, the number of launches is increasing. Whilst it may be obvious to most, launching rockets impacts air traffic routes, even if the launch site itself is within segregated airspace; the trajectory of the rockets can transit airspace of multiple states and intersect number of airways. This results in bespoke airspace reservations being implemented that airlines must avoid, generating increased track miles or delays. Increased launch numbers means increased airspace restrictions which in turn means increased disruption to the airlines; this disruption has a value, in terms of time, schedule changes and of course fuel burn. The question is, for commercial launches, who should pay for this increased disruption to the civil airline sector that is caused by a third party who is gaining commercially? Should the airlines be compensated, or the extra costs transferred to the passengers as an acceptable cost of assured access to space, or should the space access be paid for by the launchers?

For example, the impact of a single SpaceX Falcon launch in 2018 from Cape Canaveral, a purely commercial activity, required a bespoke airspace reservation stretching 1300 NM. Whilst the rocket accessed the airspace for only 90 seconds and its booster rockets splashed down 8 minutes later, the airspace reservation lasted for 3 hours. The Airline Pilots Association calculated that this lead 563 flights to be delayed by at least 8 mins and an additional 34,000 NM flown. Embry-Riddle Aeronautical University analysis suggests this would cost an airline between $\$10,000 - 30,000$ in extra fuel to avoid this airspace reservation [6].

Whilst currently infrequent in the European airspace, the Virgin Orbit launch in January 2023 required a 4 hour airspace reservation of $2,000NMx100NM$ stretching from the south coast of Ireland to the Canary Islands, impacting both the East-West trans-Atlantic flow and the North-South routes. The airspace reservation is done through the design of the Temporary Danger Area (TDA), the shape of which, and times of its activation are shared with the users (see section 2.3 for details).

2.2. Growth of spaceports

The move from state-managed spaceports to commercial entities reflects the industry's shift from a government/military led sector to a market orientated activity. As an example, the US federal government started their space launch activities in the 1940s, culminating with the establishment of Cape Canaveral Air Force Base in the 1950s. From 1996, commercial facilities began to gain prominence with now 10 non-federal space launch sites being licenced for both commercial and government related launches, from California to New Mexico. The impact the ten established spaceports, coupled with a further five being planned across the USA, are having on the commercial aviation sector is now becoming critical and a concern to Congress.

The proliferation of spaceports continues across every continent other than Antarctica, either as state or commercial run entities, as well as plans for sea launch capabilities from the North Sea in 2024. We discuss the UK in our case study. The maturity of these plans varies greatly as market confidence continues to be tested. As the launch capabilities grow, large airspace reservations will continue to cause disruption, including the sea launching spaceports.

2.3. State of the art

The International Civil Aviation Organization (ICAO), EUROCONTROL and the Federal Aviation Authority (FAA) have a close relationship with the aviation authorities who operate, or aspire to operate, a space launch capability, be it land based or air launch (e.g., large aircraft, balloons or floating platforms). Historically, spaceports have been operated by the state, but the commercial sector is becoming more enthused to develop launch capabilities to meet the market's demands for access to space. As an example, there are 8 land based launch locations under development in UK, with potentially three further sea or air launch capabilities. Across the EUROCONTROL member states' area, there are a further seven land based sites and a further four air or sea launched concepts under development.

Any launch location requires the airspace through which the rocket or launcher transits to be deconflicted from other airspace users. EUROCONTROL highlights that, in principle, this is not complicated and confirms that space launch is just another airspace closure that needs to be managed. However, the financial or operational impact of these airspace closures to the user community is not articulated. Airspace structures are designed to ensure the hazardous activity, i.e., the launch, flight and re-entry trajectory of the launcher, coupled with mitigation should the launcher fail and explode in flight, is separated from other users [7].

In Europe, airspace users are informed of the intended airspace restrictions, i.e., the TDAs, via the Aeronautical Information Regulation and Control (AIRAC) cycle[2] which promulgates the restrictions at least 3 cycles in advance. This stage allows airlines to plan their routes with the knowledge of the eventual restrictions and any conditional routes available. As the launch nears, up to 7 days ahead of launch (strategic phase), the planned flights (mainly historical) are analysed by the Network Manager[3] (NM) to understand which flights are likely to be impacted by the restrictions; the NM promulgates these restriction in the Network Operations Portal. As launch draws closer, the pre-tactical phase at Day (D)-6 to D-1, allows the NM to hone the plan further to take into account weather patterns and the anticipated air traffic demand, including these into the Airspace Utilisation Plan (AUP). The AUP promulgates the restrictions to the whole Network that covers multiple states, and their airspace (through the Flight Information Regions (FIR)), highlighting the international complexities. At D-1, one day from launch, the plan is honed even further through the Update Use Plan (UUP) with flight plans, including takeoff and landing times, coupled with routes and waypoints, finalised so as to avoid the launch activity. The last parts of the launch planning and notifications to the airspace users are described. Each state has its own requirements for planning and notifications are provided in collaboration with the NM, which facilitates the design of danger areas and communications between neighbouring FIRs. The standard operational procedures for space launches in the European airspace are still being formulated, expectations are they will be ready in a couple of years [4; 8]. A space surveillance and tracking (SST) system is a network of ground- and space-based sensors, surveying and tracking space objects [9], aiming to provide data services on space objects that orbit the Earth; there remains, however, a lack of appropriate sensors in terms of sensitivity, number and system integration. The 'SST Partnership' and the European Union Agency for the Space Programme, are working together to develop the European SST capability[4].

The US's FAA has two offices dealing with the commercial space launches: Office of Commercial Space Transportation (AST) and Office of Space Operations Integration (ATO). The AST provides experimental permits and commercial launch licences, spaceport licences and takes care of inspections and payload reviews [10], while the ATO office integrates launch and reentry operations (both commercial and non-commercial) into the National Airspace System (NAS) [10; 11]. The ATO covers 4-step process of: notification of launch (from the operator), evaluation of the launch specifications developed by the operator, decision on the parameters of launch and the protected airspace areas and airspace management plan development and distribution. The air traffic is then controlled tactically, based on the accepted plan and real-

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[2] An AIRAC cycle is 28 days.

[3] EUROCONTROL is the Network Manager.

[4] https://www.eusst.eu/.

time monitoring of launch operations that allow for the opening of the airspace as soon as the area is out of possible danger. The FAA developed the concept of operations for commercial space integration into NAS [12]. In 2022 there were 92 launch/re-entry operations, while it is foreseen that there will be 140 of such operations in 2023, in the USA only.

Early valuable modelling and simulation [13] on the impact of HAO types on air traffic in the European context, was based on two case studies, analysing delays and increased fuel consumption, without cost assessment. Extensive later work [14] analysed such impacts in the US context, through six launch scenarios, quantifying delay, additional fuel costs and *average* block-hour (strategic) operating costs. (We will compare these cost results at a high-level with our initial results, later.) Further extensive modelling and simulation of HAO impacts, on European air traffic, deployed a broad cross-section of use cases and demand scenarios, focusing on the UK-Ireland FAB[5] [15]. Various flight efficiency parameters, including additional fuel consumption and additional flight duration, were assessed, without (further) cost assessment. A key contribution we make in this paper is, therefore, to the best of our knowledge, the first aircraft-specific fuel and operating cost analysis of HAO impacts, and the first such European cost assessment, albeit with considerably more basic impact geometries than those exemplified by [14] and [15]. Furthermore, we also propose below, improved aircraft-specific impact models, which include passenger-centric costs.

3. Cost impact assessment methodology

In order to deconflict the air traffic from the space vehicle, the airspace use restrictions are put in place, by designating the areas and times during which the area is off limits for air traffic. Meaning, that the air traffic needs to either wait for the airspace to be available again, or to fly around it. Both waiting, and flying longer routes create additional costs to airlines through the cost of delay and/or the additional fuel (and time) for fly-around.

Here, we propose an initial methodology to assess the costs due to space launch airspace restrictions. First we discuss the principles of cost of delay and then we proceed to describe the initial methodology for cost impact assessment of space launches.

3.1. The principles of calculating airspace user cost of delay

Flights can experience delay for numerous reasons, like weather, winds, missing passengers, etc. Some delays are predictable, while others occur during the operations. A delay generates extra costs for the airline, from additional fuel, raised wage bills for extra staff hours, eventual passenger compensation, to increased airport charges. Longer delays have higher impact than shorter ones, and the greater the time an airline is aware of a delay, the more time it has to manage the additional costs. The delays, and their associated costs can be divided as:

- Strategic delays – which are predictable against the original schedule and occur during the strategic phase of the ATFM cycle (e.g., pre-planned closures of airports or portions of airspace).
- Tactical delays - which occur on the day of operations, and are largely unpredictable (e.g., crew resource issues, weather, ground support issues), and must be managed tactically.
- Reactionary delays - which are generated by delays on previous flights performed by the same, or other, aircraft (e.g., due to late arrival of flight, or crew, or passengers).

The delays incurred by the disruptions due to space launches, would be classified as strategic, as the airspace restrictions are published at least three AIRAC cycles before. The strategic and tactical costs of delay can be found in [16], with the most recent values in [17].

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[5] Functional Airspace Block, covering Ireland and UK FIRs.

3.2. Specific factors to consider for the temporary TDA activations

As the airlines receive the information early, in theory they have enough time to plan the TDA avoidance, which is our working assumption. We can assume the fly around would use a simple reroute, see Figure 2. The earlier in the flight the track deviation is made, the smaller the heading (θ) change needed, but potentially the longer track miles may be created.

The following formula can be used to calculate the additional flight time the aircraft would have to accept to avoid the TDA (i.e. flying the purple line to avoid the TDA):

$T_e = (\frac{W*T_o}{L}) * \frac{(1-cos(\theta))}{sin(\theta)}$,
T_e = extra time flown,
T_o = original time to be flown inside TDA (L),
L = length of the rectangle representing the TDA,
W = width of the rectangle representing the TDA.
θ = angle of the flight deviation from the original trajectory.

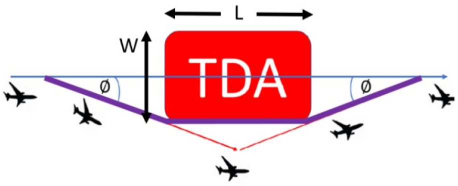

Figure 2: Geometry of trajectory deviation.

With the extra time flown, we use values from [16] strategic cost of delay tables to calculate the extra costs to the flight, due to flying around the TDA.

3.3. Selected case study - Virgin Orbit launch

The most recent launch that involved general use airspace and required restrictions was the Virgin Orbit launch, which took place on 9th-10th January, 2023. A converted Boeing 747, ‘Cosmic Girl’, took off from Cornwall spaceport, for in-flight release of the LaunchOne rocket. The rocket failed to reach the required altitude and it was lost (with its payload).

The original date set was 15th July 2022, and due to various procedural and operational delays, it was moved to October, then December of 2022, and finally to January 2023. Different TDAs were discussed and analysed. In this case study, we will apply the proposed formula to a sample of simulated flights for the ‘EUVIRGIN3’ TDA (see Figure 3 for depiction of simulated flight trajectories)[6], one of TDAs analysed by the NM during the approval process. The simulations were based on historical data, for a similar day and time (e.g., second Tuesday in August) to the foreseen activation time of the TDA.

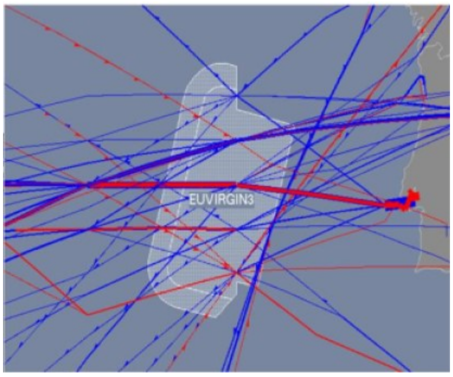

Figure 3: Case study TDA, depiction courtesy of EUROCONTROL.

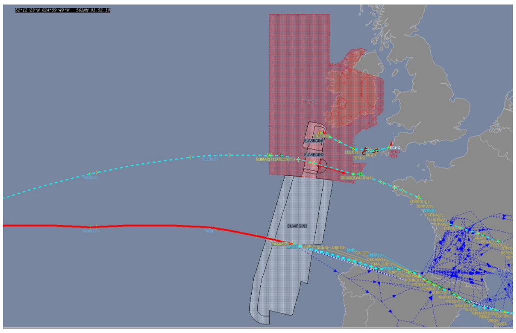

Figure 4: Actual TDA with vectored flight, depiction courtesy of EUROCONTROL.

Table 1 shows the extra time flown (T_e) and related costs (reported to 2 s.f.) for three sampled flights (for which we had ‘original’ trajectories, departure and arrival airports, scheduled times

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[6] Sample shared with the authors as a professional courtesy.

and aircraft types). Based on the calculated T_e values, and the aircraft (a/c) type, we derive values from the strategic cost tables (which include fleet operation, fuel, maintenance and crew costs [16]), to obtain the cost for different values of heading change (θ). As can be seen, the costs are not linear in time, and differ across the aircraft types. For aircraft not explicitly costed in the published tables, the authors demonstrate [16] a very good fit between costs and aircraft maximum take-off weights. If we take into account that the average en-route charge per flight in European airspace is about €900[7], the costs of extra time flown are either equal or greater, even an order of magnitude, showing that the impact can be significant, even if taken at the strategic level, which is less costly than the tactical one.

Table 1: Results for a sample of flights.

A/c type	Min in TDA	TDA size		T_e for θ change			Costs for θ change (2 s.f.)		
	T_o	W	L	10°	20°	30°	10°	20°	30°
A20N	12	310	35	9	19	28	€560	€1300	€2600
A21N	21	310	35	16	33	50	€1100	€3200	€9600
B772	21	310	35	16	33	50	€1100	€4700	€11000

The actual launch TDA covered a much larger area. However, it was possible for EUROCONTROL and Virgin Orbit to find a launch window that would have allowed appropriate access to LEO, and, at the same time, minimal disruption to air traffic. The TDA was active during 4 late-night hours, where for about 2 hours there are no flights. Otherwise, during the day a large number of flights (about 1200 each day) would cross the TDA. All flights avoided the TDA, either because of the pause in the east-west oceanic operations, being delayed on the ground, or being flown closer to the mainland to avoid the TDA. Figure 4 shows the actual TDA and the trajectory of the only flight that needed to be vectored around (upper trajectory), due to winds being stronger than forecast, bringing the aircraft across the ocean an hour earlier than expected. Whilst it is difficult to directly compare costs with other work, partly due to a lack of detailed access to the methodologies, but mostly due the absence of such work, our calculations on some of the reported scenario data from [14], gives an average strategic cost (including fuel) of approximately \$(2017) 300. The costs we report in Table 1 are rather higher, with the difference probably substantially attributable to the definition of, and focus on, 'impacted' flights.

4. Discussion and conclusions

Regarding the current frequency of planned (launch) and unplanned/uncontrolled (e.g. debris re-entry) events, the corresponding disruptions are tolerated by various impacted stakeholders. However, with a large increase in these events, particularly planned launches, and with the ATM response needing to become more dynamic, coordination with stakeholders and better *costing* of the associated impacts is vital, in order to understand both the cost-benefits of investing in future deconfliction (in addition to the safety imperative) and to decide whether and how to introduce 'deconfliction' charges. Such charges could cover the costs of providing the service, i.e. paying for the ATM-STM interface, as users already pay for existing ATM services, and to compensate other users for disruption [18]. We have also flagged the need for improved sensor technology to predict and alert for HAO trajectories (vitally reducing the costs currently associated with high levels of uncertainty), which also needs to be paid for.

In this paper we have illustrated some of the airspace user costs using a simple geometry approach to assessing TDA impacts. In future, in addition to improving the 4D geometries

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[7] Calculations based on the data on flights and collected charges from https://ansperformance.eu/

to reflect other published approaches, we could, in particular, render the model more dynamic through a shift towards *tactical* costs, including departure delays and passenger-centric costs, which will significantly drive up the costs of Table 1, and consider cancellation costs. Such a model would then not only be aircraft-specific, but also include associated passenger costs, which often dominate the airspace user costs (e.g. over fuel [16]).

In addition, it would also be necessary to include other stakeholder impacts and/or new service provisions (e.g. airport revenues; NM, ANSP controller costs; military disruption), and to consider non-cost KPIs (such as environmental impacts). With potentially significant shifts from state-managed to commercial activities (and spaceports), only such wider assessments could allow states to decide on the potential trade-offs between national interests and the requirements of international cooperation and integration.

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