Simulating the Risks of Sub-Orbital Space Flight for Air Traffic Management

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Abstract

The next decade will see an increasing number of sub-orbital space flights for both scientific reasons and for space tourism. In the longer term, these initiatives may also lead to the development of sub-orbital transportation – for instance, to support military fast response without the need for costly, high-risk local deployments. As part of the longer term planning for these flights, it is important to assess the possible risks to civil aviation and, in particular, the hazards that might arise from their interaction with controlled air space. In this paper, we present the results from integrating live data about aircraft flights using an Automatic Dependent Surveillance-Broadcast (ADS-B) server together with up to data meteorological information. The users of the system describe the performance characteristics of a sub-orbital vehicle together with the coordinates of a potential accident. The system then calculates the resulting debris field and presents a predictive model of the consequent impact on surrounding aircraft at different flight levels. The closing sections of the paper identify future directions for research to assess the safety impact of sub-orbital flights.

Introduction

Orbital flights reach a sustained altitude of approximately 100 kilometres above sea level; beyond the Karman line. In contrast, sub-orbital flights reach the edge of space but their trajectory is such that the vehicle does not complete one full orbital revolution. In the past, suborbital flights were used to test space vehicles. They have also been conducted for scientific and military purposes. The high costs and technical difficulties associated with such missions, especially using reusable launch vehicles, restricted the number of flights. However, there has been a sustained interest in wider applications including rapid transportation and space tourism, also known as ‘personal spaceflight’. Over the last decade a growing number of start-up companies have invested in the development of different launch technologies:

- Virgin Galactic is based on the SpaceShipOne technology that won the Ansari X-Prize for the first non-government organization to launch a reusable manned spacecraft twice within two weeks. Virgin Galactic has more than 500 applicants for their proposed operations from the Mojave Spaceport in California, from Spaceport America in Upham, New Mexico and Spaceport Sweden, in Kiruna. Each flight is intended to last just under three hours with a glider detaching itself from a mother ship at around 50,000 feet above sea level.

- XCOR America intends to operate from Midland Texas after previously considering both the Mojave Spaceport and Spaceport Colorado. Their Lynx rocket-plane is slightly smaller than Virgin Galactic’s VSS Enterprise; approximately the size of a small private plane. However, it is intended to have short turn-around times so that it could complete up to four sub-orbital flights within twenty-four hours. Each flight will reach the Karman line; with a flight duration of around 30 minutes. Also, in contrast to the Virgin Galactic operations, the jet powered Lynx is independent of any secondary mother ship.

- Armadillo Aerospace follows a third approach, rejecting both the rocket place concept and the use of mother ships. Their focus has instead been on Vertical Take-off and Vertical Landing with reusable rocket powered vehicles. They have completed a number of test flights, however, their commercial plans for personal space flight arguably lag behind those of Virgin Galactic and XCOR.

These companies operate within a regulatory framework that is supported by the FAA’s Office of Commercial Space Transportation (AST). This was established within the Office of the Secretary of Transportation following the 1984 Space Launch Act. In 1995, it became the only area of business within the FAA that is explicitly concerned with space. Its aims are to regulate U.S. commercial space transportation and ensure compliance with international obligations. AST must protect the public health and safety, the safety of property and national security. However, they are also charged to promote commercial space launches and re-entries by the private sector. In order to achieve these different objectives, AST can recommend changes in Federal statutes, regulations and policies. Their work is supported by the 2011 Commercial Space Launch Amendment Act (51 U.S.C. Ch. 509, §§ 50901-21, 2011) that provides the legal basis for the regulation of human, commercial space flight with a particular concern for public safety during launch and re-entry. Since 1989, they have licensed more than 200 launches and 8 commercial spaceports. The Act also creates a regulatory framework based on experimental permits for suborbital operations. Before the 2004 amendments, FAA licenses were issued for launch and re-entry. These changes were intended to encourage the development of commercial space operations by providing a faster response to any application and by supporting the development of reusable suborbital rockets (US FAA, 2005). All three of the companies listed in on the previous page now operate their suborbital reusable launch vehicles under FAA AST licenses.

In Europe, the European Aviation Safety Agency (EASA) is the closest parallel to the FAA AST. EASA provides opinions that explicitly guide the European Commission in drafting implementing rules. They publish certification specifications and applicable means of compliance which are not legally binding. EASA may also issue special conditions that adapt existing airworthiness codes for new systems. This framework supports the development of type certificates that may also be extended to sub-orbital aeroplanes if they derive support from the atmosphere during some stages of their flight. This illustrates significant differences in the ways in which Europe and the United States have sought to regulate commercial suborbital space flight. In particular, the FAA's Commercial Space Transportation Advisory Committee (COMSTAC) has argued that EASA's potential extension of aircraft-like certification for winged space vehicles is 'premature'. The costs associated with existing certification processes could damage the nascent suborbital space transportation industry. In contrast, the FAA issue launch licenses to commercial operators but do not certify their vehicles. The intention is to build up experience of commercial operations before any regulations are published. The consequences of any long term disagreement between the US and Europe would have significant consequences. For instance, companies such as Virgin Galactic, operate under the FAA in New Mexico and under EASA regulations in Kiruna, Sweden. Other operators, such as XCOR Aerospace would be in a more complex situation using launch sites in Curacao. Curacao is a 'constituent country' of the Netherlands but outside the immediate scope of EASA. There have been moves to support 'interoperability'; this implies that sub-orbital space flights will be permitted with 'minimal changes' between two or more regulatory regimes. A memorandum of understanding might then be created between EASA and the FAA to simplify the application process for commercial operators. Such an agreement would build on existing space law. In contrast, the remainder of this paper focuses on the safety implications of sub-orbital space flight for air traffic management [1].

Suborbital flights typically operate under visual flight rules (VFR). In conventional aviation, the pilot is responsible for operating their aircraft in weather conditions that must be clear enough for them to see and avoid other aircraft or ground hazards. They must be able to operate the aircraft with visual reference to the ground and must "see and avoid" other airspace users. They are responsibility for their separation and are not assigned routes or altitudes by air traffic control (ATC). Depending on the category of airspace in which the flight is being conducted, conventional VFR flights are required to carry a transponder that helps Air Traffic Control Officers to identify and track the aircraft so that they can advise other flights that may be operating under ATC supervision. Sub-orbital flights, typically, also operate in Special Use Airspace (SUA) around designated spaceports. Other airspace users are prohibited from entering these areas. In addition, Temporary Flight Restrictions (TFR) can be used to extend an existing SUA or to exclude other aircraft during operations in other areas. During the launch or re-entry of a RLV, notice to airmen (NOTAM) alert pilots and air traffic controllers to the operations and the boundaries of required airspace. These methods have proven to offer sufficient protection for the limited sub-orbital operations that have taken place in recent decades. However, the increased frequency and duration of the proposed individual spaceflights as well as the diversity of launch technologies pose new challenges. This paper does not focus on the direct integration of sub-orbital flights into controlled air space. Instead, the following pages describe ways to assess the potential safety impact of debris from sub-orbital flights on conventional aviation.

It is difficult to accurately assess the risks that suborbital debris poses for commercial aviation when we are uncertain about the performance characteristics of many of the proposed vehicles. Similarly, most of the companies working in this area have not published detailed descriptions of their Standard Operating Procedures for both normal operations and contingencies. However, the FAA calculate that an impact with debris fragments over 300 grams is likely to cause the destruction of commercial aircraft irrespective of the point of impact [2]. Smaller objects are likely to have similar consequences if they hit more vulnerable areas, including the control surfaces or fuel tanks. Concerns over these hazards were reinforced by the Columbia disaster. Damage to the heat protection led to rapid increases in temperature over the wing leading edge during re-entry. The vehicle began to break up at an altitude of 231,600 feet, traveling at Mach 23. Columbia started to disintegrate as it crossed Texas. More than 84,000 pieces were dispersed across 2,000 square miles within

Western Louisiana and Texas [3]. The resulting total debris weighed over 84,900 pounds, 38 per cent of Columbia's dry mass; the remaining 62 per cent is missing with the majority believed to have been destroyed during re-entry. In the aftermath of the tragedy, concerns focused on whether, in the future, the loss of the crew might have been compounded by injuries to people on the ground or to other airspace users. The accident report estimated the probability that the loss of Columbia might have led to ground casualties was less than 0.5 but greater than 0.05. It also stated that the worst case probability of a similar incident striking traditional aviation was 0.08. They argued that "a more detailed aircraft risk analysis should be performed using the actual records of aircraft activity at the time of the accident". The following pages present a simulation environment that can be used to conduct such studies for incidents involving the growing numbers of suborbital flights.

Modelling Sub-Orbital Debris

Debris models calculate the motion, impact location and volumes of airspace affected by falling objects [4]. They use mathematical abstractions to model the underlying mechanics including the interactions between gravitational forces as well as lift and wind velocity. Previous examples include the Debris Risk Assessment (DeBRA) risk assessment tool developed by APT Research[1]. This tool uses information about the trajectory of a reusable launch vehicles together with the potential failure mode to calculate the potential debris field. Failure modes include in-flight explosions and breakups, engine shutdown failures and malfunctions. DeBRA overlays the resulting field on population densities to assess the impact on the ground.

The Common-Real-Time Footprint (CRTF) toolset provides a probabilistic debris model for instantaneous vehicle breakup. The tool can use an initial state vector or can be tailored to particular configurations using a large number of state vectors to describe potential accident conditions with their associated probabilities [3]. CRTF uses probability distributions to model the shape and mass of debris fragments as well as atmospheric conditions, including wind speed and direction. Monte Carlo techniques are then used to characterise particular scenarios and their impact distributions. CRTF has been used by both NASA and the FAA to calculate safe flying distances during the launch and re-entry of RLVs. However, it involves proprietary source code and has not been integrated with information about the changing distribution of commercial aircraft operations. Later sections will argue that this is important when assessing the hazards posed by increasing numbers of sub-orbital flights.

The TAP (Trajectory Analysis Program) [5] lacks some of the sophistication of DeBRA and CRTF, however, it is in the public domain and can be easily ported to support a wide range of research projects. TAP models interactions between a range of parameters including the initial altitude of disintegration; initial density altitude; altitude of impact at ground level; wind velocity and direction; horizontal true airspeed at disintegration; rate of climb or sink at disintegration; the weight of the projectile; the projectile drag coefficient; projectile frontal area. These parameters are discussed in greater detail in the following section. For now it is sufficient to relaise that TAP calculates the gravitational and aerodynamic forces affecting the debris to estimate the horizontal distance from disintegration at impact; the horizontal, vertical, and total velocities; terminal velocity; the flight-path angle at impact and the ground speed of the projectile at impact including the x and z components of that velocity.

It is important to stress that there are very few models which have been specifically designed to model debris from sub-orbital flights. TAP was initially developed to help planners organise air shows, where the crowd should not be exposed to the risks of debris from the aircraft talking part. The relatively high number of previous incidents at air shows both motivated the development of TAP and provided a wealth of initial data supporting the validation of interim results. This data is often lacking for other tools. The model assumes that the aircraft suddenly disintegrates into a number of parts. It does not model multiple or progressive disintegration. Our extension of an existing debris simulator poses a number of further challenges given the forces that might characterise sub-orbital accidents [1]. We must understand the mechanical forces and environmental conditions acting on each object; these can be modelled in terms of aerodynamic and gravitational forces.

Weight is the force acting on an object due to the influence of gravity and it is, typically, calculated as the product of the object's mass and gravitational acceleration: $w = mg$. For sub-orbital debris it is important to note that gravitational acceleration decreases the further that an object is from the Earth's surface. Further complexity arises because standard operational approaches measure the weight of an object in terms of the force

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[1] http://www.apt-research.com/products/models/DebRA.html, last accessed April 2013.

it exerts when at rest on a support. However, an object in free fall exerts little force on a support. This describes the ‘weightlessness’ that is a primary appeal of personal space flight. However, being in free fall does not affect the weight according to the gravitational definition. ISO 80000-4 provides a frame of reference for the calculation of weight under local gravitational forces.

The motion of falling debris is opposed by *aerodynamic drag*. This mechanical force is generated by the difference in velocity between the solid fragment and the gaseous atmosphere. Aerodynamic drag [6] can be modelled by the following equation

$$\mathrm{F}_D = \frac{\mathrm{pv}^2\mathrm{C}_D\mathrm{A}}{2}\text{, where}$$

- F_D is the drag force.
- p is the mass density of the gas or fluid.
- v is the velocity of the object relative to the gas or fluid.
- A is the reference area.
- C_D is the drag coefficient.

The reference area is generally taken as the frontal area of the fragment, the area which is perpendicular to the flow direction. The drag is assumed to depend on the size of this area. The larger the reference area, the greater will be the drag. The drag coefficient is a variable used to characterise a range of more complex parameters including shape, flow conditions, and inclination that affect drag, for an introductory overview see [7].

Lift is a force which occurs when a moving flow of gas is turned by a solid object. Following Newton’s third law of motion the flow is turned in one direction and lift is generated in the opposite direction, perpendicular to the debris’ direction of motion:

$$\mathrm{F}_L = \frac{\mathrm{C}_L\mathrm{Apv}^2}{2}\text{ , where}$$

- C_L is the lift Coefficient.
- A is the surface area of the debris
- p is the air density.
- v is the velocity of the debris.

The lift force generated by a piece of debris is directly dependent on the debris’ shape. For example; a flat object, such as a portion of wing will generate a larger lift force when compared to cube shaped debris. A larger lift force will result in the debris having a slower velocity. Therefore the wing will fall more slowly than the cube.

Newton’s second law of motion states that the force f of a moving object with a constant mass is equal to the object’s mass times the object’s acceleration f= m*a. As such the acceleration of a debris fragment can be calculated as the net external force over the fragment’s mass. Each fragment of debris has an initial state vector which is represented by a position and velocity. An initial state vector might be altered in particular simulations to model the velocity that results from an explosion. In addition, the trajectory for a piece of falling debris is mainly defined by its *Ballistic Coefficient*. This can be calculated as:

$$\beta = \frac{\mathrm{W}}{\mathrm{C}_D\mathrm{A}}\text{, where}$$

- W is the weight of the debris fragment,
- C_D is the drag coefficient;
- A is the representative area used to calculate the drag coefficient.

The ballistic coefficient represents the weight to drag ratio. Objects with a low coefficient fall more slowly. The lower the β value then the greater impact *wind velocity* will have on the trajectory of an object.

Previous debris models have focussed on mapping the area of ground affected by a debris field or have simulated the volume of airspace that might be at risk during a range of different failure modes. Analysts must then use their judgement to determine the likely consequences for other airspace users. This raises a number of concerns when specialists in debris modelling lack the ATM expertise that is necessary to make valid assumptions about changing traffic patterns. In contrast, we were motivated to extend previous work to identify the detailed impact of suborbital debris on commercial flights. The intention was to enable users to assess whether objects would intersect with the flight path of aircraft across Europe and North America.

A number of previous projects provided the starting point for our work. The Shuttle Hazard Area to Aircraft Calculator (SHAAC) used a state vector to model the different debris fields created by scenarios involving the NASA orbiter [8]. A hazard area computed the volume of airspace affected by falling debris. This could then be overlaid on ATC displays. SHAAC could be used in two different modes. In real-time operation, it could provide tactical information during an uncontrolled re-entry, similar to the Columbia Disaster. ATCOs might then be able to use the output from the tool to redirect aircraft away from a hazard area. In planning mode, SHAAC could take multiple shuttle state vectors as input and output multiple potential hazard areas. This tool motivated our work to provide a more general application that could be configured for a wider range of suborbital flights and that might also be used with real-time flight data for conventional aircraft operations.

NASA's Future Air Traffic Management Concepts Evaluation Tool (FACET) visualises aircraft trajectories across the United States [7]. It provides researchers with an environment to test air traffic management concepts including redesigned airspace models under the impact of changing weather patterns, flight schedules, aircraft types and various climb, cruise and descent trajectories. One approach would have been to integrate FACET with generalised debris models for sub-orbital vehicles based on SHAAC. However, both would have had to be extended to account for the potential impact on European flights as well as those cross North American airspace.

Previous simulators tend to have relied on stand-alone, monolithic architectures. This provides significant strengths; they are optimised to rapidly provide results without suffering from the reliability constraints that can arise from more distributed models. In contrast, we chose to base our implementation around a web services model so that we could draw on live data from a number of different applications. This approach offers great flexibility as common interfaces help us to choose between data from a range of different sources. However, it does create problems in ensuring timely access to remote services. In particular, our simulator was developed to draw on real-time flight data, a geographical information system and a live meteorological service providing data on the wind speed and direction that influences debris dispersion. The following sections will reiterate the benefits of a modular architecture by describing the strengths and weaknesses of existing data sources for modelling the impact of sub-orbital debris on conventional, commercial aviation.

Our work focussed on integrating an implementation of the TAP model with live flight data, for instance from datalink technologies including Automatic Dependent Surveillance – Broadcast (ADS-B) servers. Aircraft use the ADS-B protocol to send out updates on their velocity and position at least once every second. In order to do this, they use a range of on-board equipment, including enhanced GPS receivers. At present ADS-B is optional, however, it is likely that most commercial aircraft will be required to carry this equipment following the implementation of the NextGen and SESAR initiatives. The use of this technology avoids the overheads associated with the maintenance of ground based radar systems and offers increased accuracy in areas of sparse coverage by conventional radar infrastructures. The chosen server provided a standard API for real-time access to live data on aircraft across 45 countries. The server integrates information from another 50 independent sources covering both private and commercial traffic. A limitation of this aspect of our implementation is that there can be delays while the simulator loads flight plan and trajectory information across busy areas of airspace – for instance above major hub airports. However, each run of a simulation can be cached for later replay. The development of a generic API supports the substitution of alternate servers or the integration of multiple data sources in future versions of our simulator.

The second technology to be integrated through a web service model is intended to support the visualisation of our simulations. A three dimensional satellite imagery and mapping service was included. This enables users to visualise the four-dimensional trajectory of flights as they pass across particular volumes of airspace. Users specify the coordinates and altitude that they wish to view and the aircraft are presented against a background that can include cartographic details or photographic representations of the ground at a number of different levels of resolution. This is important when assessing the impact of debris from any mid-air collision on ground based structures or population centres. A limitation of the present implementation is that the servers we use will provide access to photographic and cartographic tiles that are then stitched together in our visualisation. In the future, the modular approach might be used to integrate more general GIS tools so that users can gain accurate information about population densities rather than the simple visual representation provided in the initial version of the tool.

The final component of the simulator provides live information on wind speed and direction. Previous sections have explained the impact that such factors can have upon debris dispersal. This arguably poses the greatest challenges to our design. There are few (no?) reliable sources of live wind speed data at the altitudes we must consider in this work. It is, therefore, possible for the user to manually enter an approximation for this data. However, there are a number of live meteo services that model expected conditions calibrated using a small number of observations that are taken each day using radiosonde balloons. These are, typically, released well away from active flight paths for obvious reasons but it is this data that is used to calibrate the models used by most Air Traffic Management companies. In the future, however, it is likely that we will have a more accurate and complete model of live wind speeds and directions using data derived from aircraft on-board systems, for instance using ADS-B down-links. Further limitations include the lack of lateral corrections for wind shift. While this is reasonable for aircraft in the troposphere it cannot be sustained for RLVs operating at higher altitudes in the stratosphere and mesosphere where there is a greater potential for sudden wind shifts.

Visualisation and Validation

Previous sections have described users can enter the operating characteristics of a sub-orbital RLV together with a location and altitude for a potential accident. The TAP model is then used to predict the descent of the potential debris field using live meteorological information. This airspace volume is then examined in real time to determine whether it intersects with the flight-path of aircraft in the vicinity. The results are provided in real-time using a 4D model, textual feedback is also provided at the end of each run describing the potential impact on aircraft. The present implementation does not yet provide accurate feedback on the knock-on consequences for people on the ground. Figure 1 illustrates the use of the simulator.

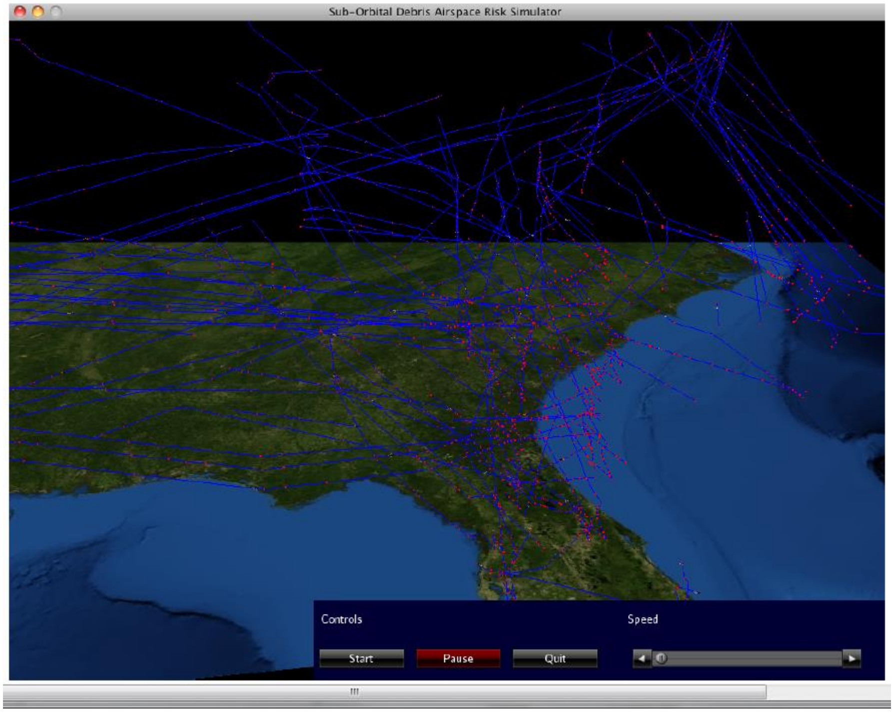

Figure 1 – Screenshot from our Sub-Orbital Debris Simulation Model

This project demonstrated what can be achieved through the integration of public information resources using web service architectures, building on the work of the FACET and SHAAC projects. However, it raises important questions about the difficulty of validating work in this area given limited experience of sub-orbital accidents and the hazards associated with potential growth in this area. The starting point was to use the most detailed data available for any previous incident. We, therefore, configured the simulator using data from the Columbia accident report. As discussed previously, the TAP debris model was not intended to model orbital break-up. However, the debris field created by Columbia is known to be around 350 miles in extent. Our implementation of the TAP model with a live weather feed estimated that the debris would disperse up to 336 miles from the break-up point. Further work is required to confirm this preliminary assessment. Equally, our simulation is intended to provide indicative feedback across a range of different scenarios. The aim is to provide a low fidelity debris model using a modular design so that components, including meteorological models and flight-path data, can be replaced as more accurate sources become available.

A key objective is to develop a reconfigurable environment that can be used provoke discussion about the risks of sub-orbital flight at various locations around the globe. We have, therefore, conducted a number of usability trials. Participants were asked to configure the simulator with the performance characteristics of a sample of the suborbital vehicles mentioned in the opening paragraphs of this paper. They were then asked to enter a sub-orbital trajectory to simulate incidents occurring at different locations around the globe. Initially we focused on the airspace above three of the US space ports. Subsequent trials focussed on more pathological scenarios – including an accident in the airspace above Miami International Airport. A ‘think aloud’ protocol was used to identify significant usability problems during these sessions. Several problems emerged – for example, it was difficult for users to identify an appropriate resolution when trying to view the relatively small volume of airspace affected by a sub-orbital incident and at the same time maintain a sufficiently wide view of other commercial and private airspace users. In the future, we intend to support users’ situation awareness through the use of split screens providing both a wider area view and a detailed model of the debris as it descents through the airspace. Other users commented on the delays, mentioned previously, that occur in loading aircraft data from the remote servers. These can be addressed by downloading flight data prior to running the simulator; providing a near real-time model. Alternatively, we can limit start-up delays by exploring the use of alternate servers for flight data. In addition to the usability study, we conducted an empirical evaluation of the impact that using our simulator had on the users’ perception of the risks associated with sub-orbital flight. We achieved significant results showing that interacting with the simulator reduced the participants perceptions about the risks posed to other airspace users.

Conclusions and Further Work

This paper has focussed on the architecture and design philosophy behind a simulator to assess the impact of sub-orbital flights on commercial and private aviation. We have not presented detailed results from the application of the system because we have a number of remaining concerns about the veracity of the models we have used. The most obvious weaknesses focus on our use of the TAP model – this was intended to simulate the dispersion of debris from conventional aircraft. We chose to base our initial work on this approach because the underlying algorithms are in the public domain – hence we could customise the parameters to represent the performance characteristics and trajectories for a range of sub-orbital operations. However, this approach has obvious limitations – for example when modelling the Vertical Take-off and Vertical Landing techniques proposed by Armadillo Aerospace. The modular approach used in our implementation supports the development of our debris model – this is essential given the uncertainty that remains over the precise nature of future sub-orbital operations.

Similar comments can be made about our use of live wind speed and direction data. More accurate models can be developed to reflect discontinuities through the troposphere, stratosphere and mesosphere. This is non-trivial. For instance, the mesosphere lies above the stratosphere and below the thermosphere – above the maximum altitude for conventional aircraft but below the Karman line. Hence very little is known about the meteorological conditions at this altitude. In particular, the characteristics of density shears remain an active topic of scientific research. More is known about the effects of atmospheric tides and gravitational waves; which have a more significant effect at this altitude. Our initial work could be extended to account for these influences on dispersion. However, it remains to be seen whether the benefits yielded by the introduction of these factors would justify the increase in complexity associated with our initial models.

An important strength of our approach is that we can simulate the impact of debris on flights in real-time. This creates some performance concerns as we sample data from servers in different locations around the globe. Some of these issues can be addressed by acquiring location information and flight plan data at the start of each run, then using interpolation to predict the location of aircraft during the limited intervals in which debris falls across a volume of airspace. This would create problems if aircraft changed their flight path during that time. Again, however, this compromise would be acceptable in a low fidelity approach given the consequent increase in performance. As usual in design a trade-off must be made, in this case between usability and flight path accuracy. The update of flight plan data raises a more general issue. Our simulator relies on Air Traffic Management surveillance data – it does not account for any interventions by ATCOs in response to warnings about sub-orbital debris. We would argue, however, that the low-cost, modular and limited fidelity approach embodied in our design can help planners and safety managers identify scenarios to be considered in full-scale ATM simulations before sub-orbital flights are approved.

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