

# COMPUTER SIMULATION AND ANALYSIS TOOL FOR AIR AND SPACE TRAFFIC INTERACTION RESEARCH

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## Abstract

Driven by anticipated increase in satellite deployments and corresponding increase on space-launch demand, numerous domestic and international government programs as well as several “start-up” private ventures have been formed to develop launch vehicles that will provide less expensive alternatives to the current fleet, including numerous reusable launch vehicle concepts. The different launch-vehicle concepts are expected to have different operational characteristics, and thus different impact and requirements on the National Airspace System (NAS). This paper describes a set of computer analysis capabilities being developed for the study of air traffic management issues related to the space operations. NASA already has the *Future ATM Concepts Evaluation Tool* (FACET) for evaluation of advanced technologies on the air traffic over the continental U.S. The computer tool described in this paper builds on FACET to include the capability to model and analyze space-flight operations within the NAS. Specifically, it includes an extensible model database for inclusion of future launch and return vehicle models for simulation and analysis; modeling of new reserved airspace definitions; functionality for analyzing launch/return operations and potential debris fallout; and more powerful visualization capabilities. The computer tool will be instrumental for studying the interaction of air and space traffic with regard to such issues as air traffic control, spaceport operations, airspace environments, automation and decision-support tools, and communication, navigation, and surveillance.

## Introduction

Driven by consumer demands for information services including mobile telephony, data communications, remote sensing, etc., the world has witnessed a considerable growth in satellite deployments. This trend is expected to continue in the foreseeable future, leading to a corresponding increase in demand on space launches. In response to the predicted increasing demands on space launches, numerous domestic and international government programs and several small “start-up” private ventures have been formed to develop launch vehicles that will provide less-expensive alternatives to the current fleet.

In the US, the 1994 Presidential Directive “National Space Transportation Policy” (NSTP) has evolved into two major programs: the NASA Reusable Launch Vehicle (RLV) Program and the DoD Evolved Expendable Launch Vehicle (EELV) Program [1]. While the EELV focuses on cost reduction through consolidation of launch vehicle families and operation infrastructure, and standardization efforts, the RLV program considers new vehicle technologies beyond the first-generation RLV — the Space Shuttle, which has become so expensive to operate that it is limited mostly to building and supporting the International Space Station (ISS). The 1996 National Space Policy identified NASA as the lead agency for research and development in civil space activities, reinforcing its commitment to develop a next-generation RLV. In the fall of 1999, NASA developed the Integrated Space Transportation Plan (ISTP) [2] to lay down the road map for near-term Space Shuttle enhancement and far-term RLV development. A central component of ISTP is the Space Launch Initiative (SLI) [3], which includes a 2<sup>nd</sup> Generation RLV Program with the goal to substantially reduce technical and business risks

associated with developing safe, affordable, and reliable RLVs. These government-supported launch-vehicle developments and other privately funded commercial launch-vehicle development ventures add a multitude of different launch-vehicle concepts that will have different impacts and requirements on the National Airspace System (NAS).

To address efficiency and safety issues associated with the ever-increasing air traffic, NASA and the Federal Aviation Administration (FAA) have engaged in advanced technology development for air traffic management (ATM). This demand for access and use of national airspace is further compounded by the anticipated growth of commercial space transportation. The use of RLVs is expected to gain popularity for economic and environmental reasons, resulting in the NAS having to deal with the return flights as well as the launches. Furthermore, many of the RLV concepts advocate space operations to and from spaceports which potentially situate in-land, leading to questions of space operations involving supersonic flights over populated areas. In view of these reasons, NASA and FAA need to extend their ATM research to address space flight traffic in the national airspace. The research programs will need to address the increased frequency of space access, the variety of space vehicles, and their operational impact.

In addition to being the nation's air-traffic-service provider, FAA, under the former Commercial Space Launch Act, also has the responsibilities to issue Launch Operator's Licenses for commercial launches of orbital rockets (e.g. Atlas, Delta, Taurus, Athena), air-launched rockets (e.g. Pegasus), and suborbital sounding rockets (e.g. Black Brant, Starfire). The FAA has also been authorized to license reentry operations, in anticipation of the popular use of RLVs [4][5].

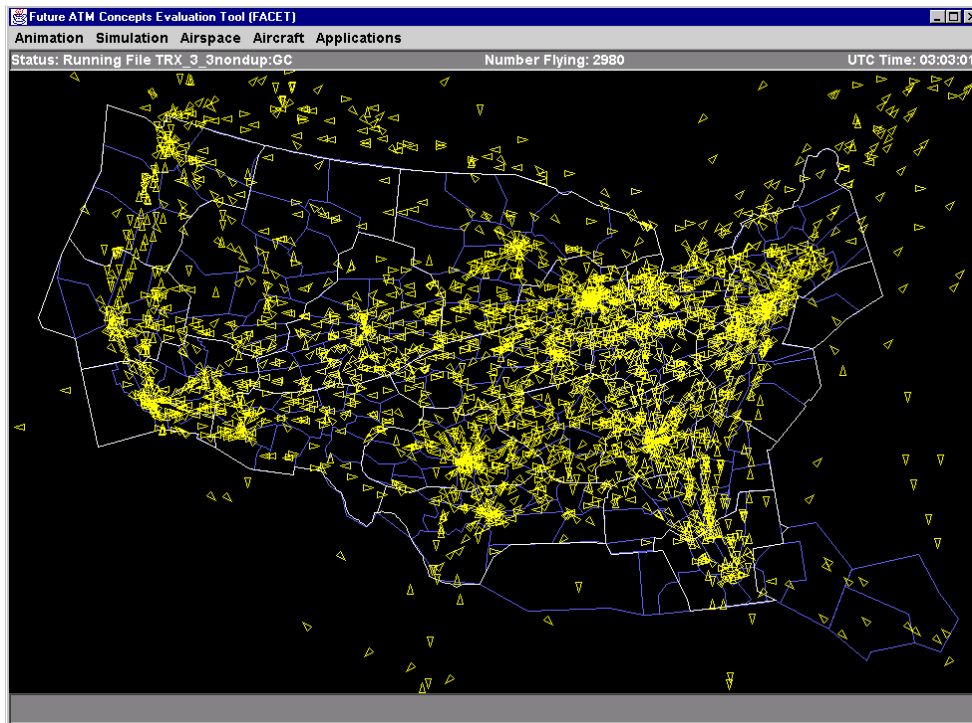
FAA began developing a concept of operations for an integrated *Space and Air Traffic Management Systems* (SATMS) to address the integration of frequent, unconventional flight profiles intrinsic to space launch activity into a NAS currently optimized to serve the needs of transport aircraft. SATMS represents a conceptual

“aero-space” environment in which space and aviation operations are expected to be seamless and fully integrated in a modernized, efficient NAS. An initial step in the SATMS evolution is the development of the instrument “CONCEPT OF OPERATIONS for Commercial Space Transportation in the National Airspace System” (CST CONOPS) since 1999, with the most recent version published in 2001 [6]. The CST CONOPS discusses the requirements in technological advancement in the areas of communication, navigation, surveillance (CNS) and decision support tools, and in operational initiatives including Free Flight and airspace re-design.

To address the need to understand the implications of new launch and return vehicle concepts and proposed spaceports on the NAS, the Air and Space Traffic Interaction Research (ASTIR) program has been initiated with support from NASA to develop a set of analysis tools for studying the effects of the space vehicles and their potential operational characteristics. This report discusses the conceived ASTIR tools, with the understanding that they represent work in progress. Specifically, they build on the capabilities of the *Future ATM Concepts Evaluation Tool* (FACET) [7], a computer program developed by NASA for evaluation of advanced air traffic management (ATM) technologies as applied to the air traffic over the continental U.S. The resulting augmented version of FACET — aptly named *Configurable Airspace Research and Analysis Tool* (CARAT) — is expected to provide useful functionality for studying the interaction between air and space traffic, with potential applications in launch licensing, spaceport licensing, launch-operation tradeoff analysis, and air traffic management.

### ***Future ATM Concepts Evaluation Tool (FACET)***

FACET has been developed at NASA Ames Research Center to provide a fast-time simulation capability, initially to support the development and advocacy of decision support tools (DSTs) for the extended terminal area. Specific objectives of FACET are to:



**Figure 1. Example of FACET Display Showing Traffic Flow over the US**

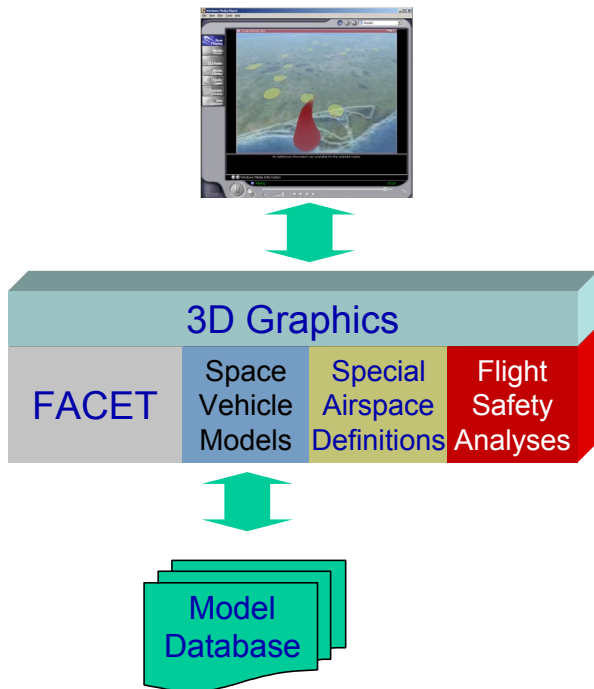
- provide a test bed for exploration of new DST concepts in a realistic air traffic environment,
- enable evaluation of potential improvements to operational performance,
- enable quantitative evaluation in terms of metrics of delay, predictability, flexibility, complexity, and effects at local and national levels.

FACET can simulate air traffic across the entire United States. It is designed using a Java front-end with a C backbone: the interactive graphical user interface (GUI) is written in Java while the remaining algorithms are implemented using the C programming language. Its Java-based GUI is shown in Figure 1. The program can simulate aircraft flying according to flight plans, with great-circle guidance and navigation between waypoints executed in a manner similar to that using Flight Management System (FMS). FACET has several large databases including airspace definitions for low, high and super-high sectors of every Air Route Traffic Control Center (ARTCC) in the U.S. The software includes data of all “Victor” airways and jet routes along with the locations of nav aids, fixes and waypoints for the

entire country. Its airport database consists of approximately 15,000 airports in the U.S. and abroad. In addition, FACET contains a database of 60 aircraft performance models and an equivalence list for all the different types of aircraft recognized by the FAA. FACET is a powerful tool for studying real-world problems due to its ability to interface with the Host Computer or the Enhanced Traffic Management System (ETMS), to allow analyses based on real, live data.

### **Configurable Airspace Research and Analysis Tool (CARAT)**

The Configurable Airspace Research and Analysis Tool (CARAT) builds on FACET by augmenting it with enhancements to include the space-operation domain, and to make it more easily configurable by the user. Specifically, the enhancements are intended to enable the use of the augmented FACET for studying the impact of space launch and return vehicles in the NAS. Figure 2 illustrates the functional components of CARAT. CARAT supplements the original FACET program with four additional components. These include three components to support quantitative analyses — Space Vehicle Models, Special Airspace



**Figure 2. Functional Components of CARAT**

Definitions, and Flight Safety Analyses — as well as a 3-dimensional (3D) graphical capability to support qualitative visualization of the airspace and traffic interaction. The features of these four major components of CARAT are discussed in the following sections.

### Space-Vehicle Model Implementation

With the high cost for operating the Space Shuttle, it was hoped that a new RLV would ultimately replace the Space Shuttle and the EELVs. Budgetary constraints would prohibit the full funding of the Space Shuttle, the ISS, as well as the full-scale development of an RLV. In 1996, NASA initiated the X-33 Project for demonstration with suborbital flights of technologies for a single-stage-to-orbit (SSTO) RLV. The program was terminated in March 2001 in view of programmatic and technical mishaps [8]. As NASA moves forward to re-evaluate its RLV strategy, other RLV technology demonstration programs have also been affected, and the contract on X-34 development also terminated in March 2001.

As the NASA RLV program was experiencing its difficulties, the DoD EELV program was not without snags either. To ensure that there would be

viable launch-vehicle alternatives, NASA in late 1998 launched a Space Transportation Architecture Study (STAS) to involve the industry in identifying alternatives for launch vehicles to replace the Space Shuttle, and the upgrades necessary to maintain the Space Shuttle until such a replacement is available. The findings from STAS suggested the focus on RLV systems based on two-stage-to-orbit (TSTO) concepts to lessen the demand on risky technologies. In the fall of 1999, NASA developed ISTP [2] with SLI [3] as a central component, which includes a 2<sup>nd</sup> Generation RLV Program with the goal to substantially reduce technical and business risks associated with developing safe, affordable, and reliable RLVs. The idea is that the 2<sup>nd</sup>-generation RLV will be developed and owned by private industry, of which NASA and DoD will be customers for launch services.

Numerous private companies participated in SLI by advocating their unique RLV concepts, which constitute part of a substantial number of commercial RLV programs. The following is a sample list of these commercial programs [9]:

- Second Generation Reusable Launch Vehicle (K2GenRLV) — Kelly Space and Technology
- K-1 — Kistler Aerospace Corp.
- Pathfinder — Pioneer Rocketplane
- Roton — Rotary Rocket Co.
- SA-1 — SPACE ACCESS<sup>®</sup>, LLC
- Space Cruiser System — Vela Technology Development
- VentureStar<sup>™</sup> — Lockheed Martin Corp.

Development of new launch vehicles is inherently costly, and it should not be surprising if any of these programs turns out to be financially unviable. Nevertheless, this list shows the variety of vehicle concepts, e.g. the Kelly K2GenRLV is a tow-launch concept that depends on a B-747 to tow the launch vehicle to 20,000 ft for launch, while the Kistler K-1 looks more like a conventional ELV but uses parachutes and airbags for return of the stages. CARAT is designed to be sufficiently flexible to accommodate these and other potential launch-vehicle models.

The variety of launch and return vehicle concepts being considered precludes the use of a single vehicle model to represent them all. CARAT includes an initial library of models to represent most of the potential vehicle designs. Models of new vehicle designs can be prepared either through modification of the existing models, or as completely new implementations. In any case, the new models can be included for access by CARAT by depositing them in a configurable model database as illustrated in Figure 2.

Most of the new RLV concepts involve multiple stages. Table 1 suggests a possible breakdown of the stage configurations for some of the launch-vehicle concepts discussed above. Assuming each staging event separates the pre-staging vehicle configuration into two new configurations, a launch vehicle composed of  $N$  stages would give rise to  $2N - 1$  configurations. Each of these configurations would require its own model implementation.

of a launch-vehicle concept using the Kelly K2GenRLV as an example. Here Stage 0 refers to the tow aircraft — a B-747 aircraft — which would tow the spacecraft to some altitude before releasing it. After the spacecraft flies out of the atmosphere and separates into two vehicles, Stage 1 would return to the launch base while Stage 2 would proceed to orbit. The return trip of Stage 2 may start at a much later time, and hence it is unlikely for this return trip to be studied within the same simulation run of the launch analysis. If necessary, the Stage 2 return mode may be simulated using a different model to focus on the return

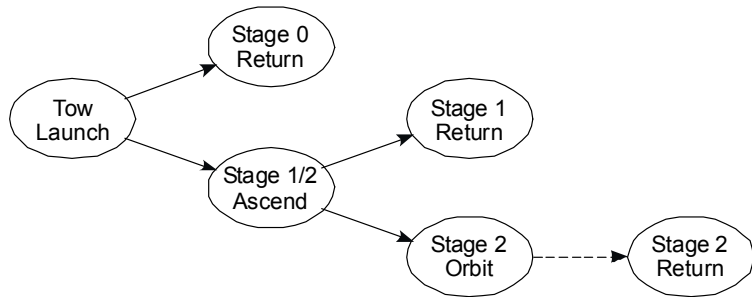


Figure 3 illustrates the staging sequence

Figure 3. Example of Launch-Vehicle Staging Sequence

Table 1. Flight Modes of Vehicle Stages for Sample Concepts

Launch Type	# Stages	Vehicle Concept	Launch Stages	Return Mode
Surface	SSTO	VentureStar/X-33	Rocket	Glide
		Roton	Rocket	Rotor
	2STO	Kistler K-1	1. Rocket	Parachute/Airbag
			2. Rocket	Parachute/Airbag
	3STO	Zenit 3SL	1. Rocket	Expendable
			2. Rocket	Expendable
3. Rocket			Orbital	
Air	2STO	Space Access SA-1	1. Hybrid	Powered
			2. Hybrid	Powered
	2SSO	Space Cruiser System	1. Airbreathing	Powered
			2. Hybrid	Powered
	3STO	Pioneer Rockplane Pathfinder	0. Aerial Refuel	Powered
			1. Hybrid	Powered
		Kelly K2GenRLV	2. Rocket	Orbital
			0. Tow	Powered
	4STO	Pegasus	1. Hybrid	Powered
			2. Rocket	Orbital
			0. Captive	Powered
			1. Rocket	Expendable
		2. Rocket	Expendable	
		3. Rocket	Orbital	

characteristics of the vehicle. The object-oriented implementation of CARAT allows the model software to communicate a staging event to the simulation process, so that CARAT can properly terminate the pre-staging model object, and instantiate the two model objects representing the vehicles after staging. The vehicle state of the two new models is specified automatically based on the state of the pre-staging vehicle.

Different stages of a launch vehicle can be modeled from a collection of a few common vehicle-model modules. Figure 4 contains a generic block diagram of a launch-vehicle module. It includes position ( $r$ ), velocity ( $v$ ) and mass ( $m$ ) as the basic state variables. The acceleration ( $a$ ) depends on the propulsion and aerodynamic properties of the vehicle module.

The vehicle can also include guidance and control functions specific to the vehicle and desired flight profile. These functions, in the case of aircraft in the NAS, are represented by the flight plans in the FACET environment. For launch/return vehicles, the guidance and control functions will need to be specifically defined to accomplish the space operation. The ATC function represents possible communication with Air Traffic Control, which may issue clearances to coordinate traffic for the cases where the spacecraft have the capability to respond to clearances under positive ATC.

### Special Airspace Definitions

Traditional airspace policy for separating air traffic from space operations involves the use of Special Use Airspace (SUA). In anticipation of

future launch-vehicle capabilities and launch rate, new airspace structures within the NAS have been suggested to enable space-vehicle operations [6]:

- *Space Transition Corridors (STCs)* can provide dynamically reserved and released airspace that allows space vehicles to transition through the NAS. STCs are selected and determined based on the performance characteristics of the vehicle and overall safety considerations. They can be tailored as mission needs or ATC needs dictate, and can provide more flexibility than today's SUA.
- *Flexible Spaceways* are similar to today's airways and jet routes and can serve traffic transitioning to and from space. These are dynamically designated to meet specific mission objectives, such as transitioning to airborne launch points, aerial refueling, etc. Depending on the mission and vehicle profile, spaceways may be used in conjunction with an STC to segregate different types of missions, to concurrently accommodate different mission phases (e.g., launches vs. re-entries), and to ensure safety in case of contingencies.

Space launches generally involve a nearly vertical, high-acceleration ascent that precludes the use of positive ATC in view of the tight constraints on the launch window and trajectory profile. For vertical launches, this high-performance ascent begins on the surface, while vehicles that depart horizontally may transition through the NAS to an airborne launch point, i.e. the point at which the vertical ascent is initiated. The vertical ascent of all missions is accommodated through use of an STC. Therefore, the STC for vertical departures extends

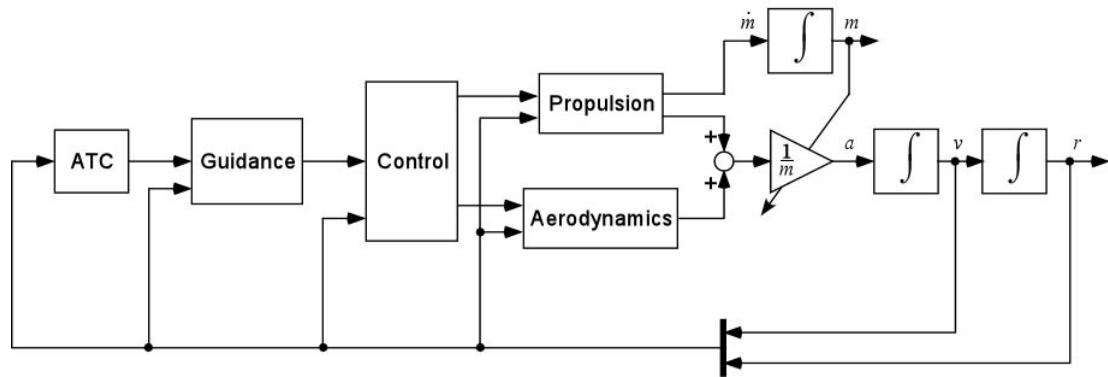
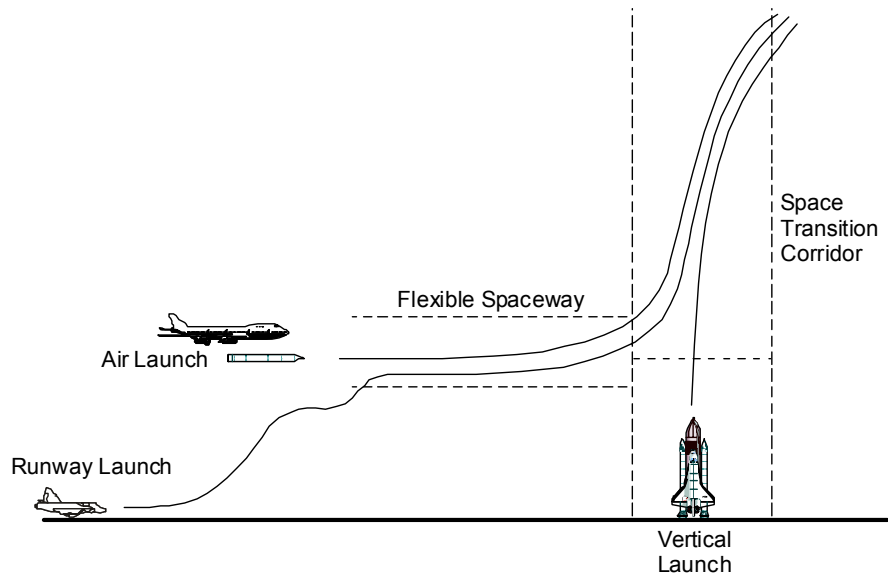


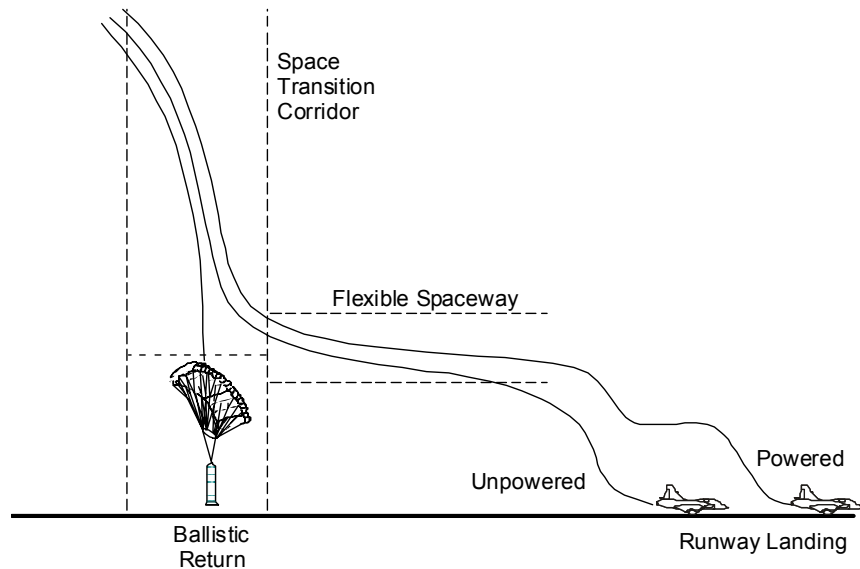
Figure 4. Generic Block Diagram of Launch-Vehicle Module

from the surface to the upper limit of the NAS<sup>1</sup>, while the conventional portion of the trajectory for horizontal departures may be handled either with an STC or through positive ATC. If positive ATC is used, the vehicle is cleared on flexible spaceways to the point at which the vertical ascent begins. The mission is then protected by an STC to the upper limit of the NAS. Figure 5 illustrates the possible use of STC and flexible spaceway for launch operations, while Figure 6 illustrates these concepts for return operations.



**Figure 5. Reserved Airspace for Different Launch Concepts**

From the point of view of CARAT development, the traditional SUA, STC, and flexible spaceway all serve similar purposes to define separation for the air traffic. They merely differ in the physical dimensions (i.e. shape, size) and the duration over which the airspace is reserved. Implementation of these airspace models in CARAT will include functions to support analysis of their impact on the air traffic and potential airspace violation of the air traffic in these regions.



**Figure 6. Reserved Airspace for Different Return Profiles**

## Analysis Functions

CARAT has been designed to host a comprehensive set of analysis tools to study the interaction between space operations and the air traffic, and to enable trade-off studies of ATC and space-operation options based on balancing the multiple objectives of benefit maximization and cost minimization, while maintaining an acceptable level of safety. The basic analysis capabilities are described in the following subsections. Based on these capabilities, CARAT will be able to support more complex

trade-off studies, including the possibility to optimize space operations with respect to its effect on the air traffic. Studies can be designed to determine the optimum launch window, flight profiles, or launch locations, etc.

## Impact of Space Operation on Air Traffic

The available air traffic simulation functionality of FACET augmented with space-vehicle models can already support basic analysis functions for studying the interaction between space

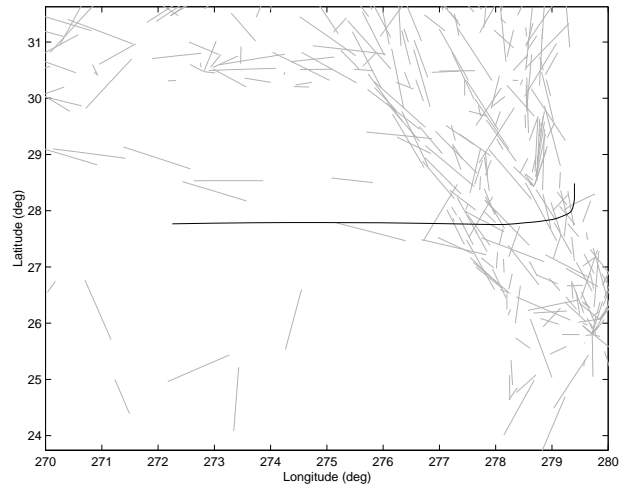
<sup>1</sup> CST CONOPS [6] suggests the specification of an upper limit of the NAS to demarcate the FAA's operational responsibilities.

operation and the air traffic. Examples of such analyses include:

- Amount of air traffic requiring diversion to avoid conflict with space operation
- Results of air traffic re-routing
- Consequential air traffic delay

To illustrate these analysis capabilities, Figure 7 shows the simulated trajectory of a space vehicle flying eastbound followed by a left turn to return to Cape Canaveral in Florida, similar to the return profile of the Space Shuttle. Overlaid in this figure are aircraft trajectories over the same time interval. These basic simulation results enable the identification of flights that may interfere with the space vehicle's separation minimums or reserved airspace, as the case may be. In consequence, these flights would require re-routing in order to avoid conflict with the return operation.

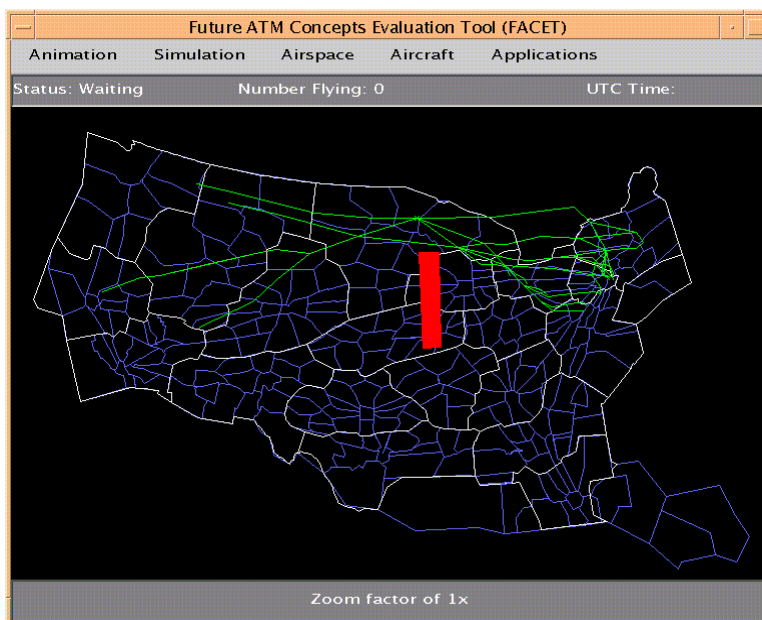
If the space operation dictates the use of reserved airspace over a period of time determined by the launch window, FACET has built-in capability to compute the re-routed trajectories for the air traffic to avoid the reserved airspace. Figure 8 illustrates the re-routing results from FACET for directing a few flights around a user-defined region. This capability is useful for studying re-routing due to space operations as much as other factors such as adverse weather. The capability together with air



**Figure 7. Sample Trajectories for Return Vehicle and Aircraft**

traffic conflict detection and resolution enable the study of re-routing beyond the primary conflict, i.e. it can include secondary conflicts caused by resolution of the primary conflicts, etc.

Results of the required air traffic re-routing can be used to determine the cumulative delay of the aircraft, thus providing one of the cost factors associated with the tradeoff analysis of integrating frequent space operations into the NAS standard procedures.



**Figure 8. Sample Air Traffic Re-routing Results**

## ***Flight Safety Analysis***

### **Airspace Violation**

With the operational procedures for space operations encoded into the space-vehicle models, the augmented system can be used to detect potential airspace violations of the space operation by the air traffic. Airspace violations can be studied as two different types:

- An aircraft violating a reserved airspace, or
- An aircraft violating a separation minimum, i.e. separation from the space vehicle.

Conceptually, violating a separation minimum will be more dangerous than violating a reserved airspace. Because an aircraft must be separated from a launch vehicle based on the hazardous effects or potential effects of the launch vehicle, violating such a separation minimum will introduce the aircraft to risk. CARAT can model the hazardous effects or potential effects of a launch vehicle, thereby defining the separation minimums that must be observed around a launch vehicle. With conventional airspace reservations, an aircraft can often fly safely through a reserved airspace because more airspace is reserved than is necessary to separate aircraft from the hazards of a launch vehicle.

With the space-vehicle model and airspace definition capabilities introduced into FACET as CARAT augmentation, these types of violations can be determined using the simulation function and comparing the aircraft locations along the trajectories with the reserved airspace or separation minimums.

### **Potential Damage due to Space-Operation Debris**

Since many of the new RLV concepts allow the RLV to take off and land like a regular aircraft, a notion has emerged suggesting that there ought to be a lot more flexibility in building spaceports from which these RLVs can operate to and from, thus easing the limitations on the launch sites. On the other hand, launch vehicles traditionally have reliability substantially below that of commercial aircraft; hence being able to fly like an aircraft does not automatically imply that the new RLV concepts can operate as safely as any other aircraft. For licensing launch sites and individual launches, FAA

has specific rules that need to be followed for verifying the effect due to any launch mishap on the air traffic and population.

The licensing of a launch site needs to follow the Licensing and Safety Requirements for Operation of a Launch Site set forth by the FAA as 14 CFR Part 420 [10]. Shortly after the release of Part 420, the FAA published a Notice of Proposed Rulemaking (NPRM) for “Licensing and Safety Requirements for Launch” as NPRM 14 CFR Part 417 [11], which deals with the requirements for obtaining and operating under a commercial launch license. Both of these sets of requirements cover debris fallout in case of a launch-vehicle breakup.

For instance, in 14 CFR Part 420, the rules require the calculation of a launch corridor from the proposed launch site, and verification that the expected casualty ( $E_c$ ) due to a catastrophic event from the launch can remain within  $30 \times 10^{-6}$  along the launch corridor. Computation of the launch corridor requires a certain level of rough estimation of the effect of debris fallout resulting from potential vehicle breakup. The formulation basically deals with a statistical debris field descending from the point of vehicle breakup, expanding as a function of the statistical wind speeds, which vary according to altitude according to historical data provided in [12]. With the launch corridor determined, computation of the expected casualty is based on population data obtained from the Global Population Distribution (1990) [13] published by the Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory.

Whereas the licensing rules for a launch site in Part 420 involves a relatively simple formulation for determining the debris fallout history, the proposed rules in Part 417 for individual launches involve substantially more sophisticated modeling of the debris fields. For instance, the computation in Part 420 is based on a single ballistic coefficient for the debris, while that in Part 417 requires the debris segments to be categorized into fragment classes, resulting in multiple debris fields. Furthermore, the wind effect assumed in Part 420 includes no knowledge of wind direction and is based only on statistical wind speed, while that in Part 417 is based on more precise wind statistical

data involving both wind magnitude and direction. All in all, the safety analysis formulations in Part 417 are more detailed, and are expected to produce more accurate and consequently less conservative damage assessment.

The current design of CARAT includes the implementation of the debris models suggested by both Parts 420 and 417, so that the final system can support the quantitative assessment of the launch operations to verify their compliance with these rules. The software is designed to be flexible in anticipation of future changes in the rules, since the rules are expected to evolve with new technological and other concerns.

### 3D Graphical Visualization

To complement the quantitative analysis capabilities, CARAT's 3D graphics capability provides the means for qualitative visualization of the results. When dealing with the air traffic, a 3D graphical visualization capability does not seem particularly attractive since the aircraft are relatively small compared to the usual separation of 5 nmi. Such a capability is somewhat more useful when it is used to explicitly display the 3D regions corresponding to the separation minimums of the flights, showing separation violation when any two such regions come into contact.

In the study of space operations in the NAS, 3D visualization is particularly valuable in showing the substantially larger separation-minimum region of the space vehicles, and for visualizing the debris fallout effect from potential vehicle breakup. This type of qualitative capability will help to identify critical areas that can be improved when the quantitative analysis results reveal that the licensing rules are violated.

The following is a list of the 3D visualization functions being developed for CARAT:

- Display of air traffic, with option for displaying separation minimums for assessing separation
- Display of space-vehicle trajectory, with option for displaying its separation minimums
- Display of special airspace reserved for space operations, e.g. STC, flexible spaceway, etc.

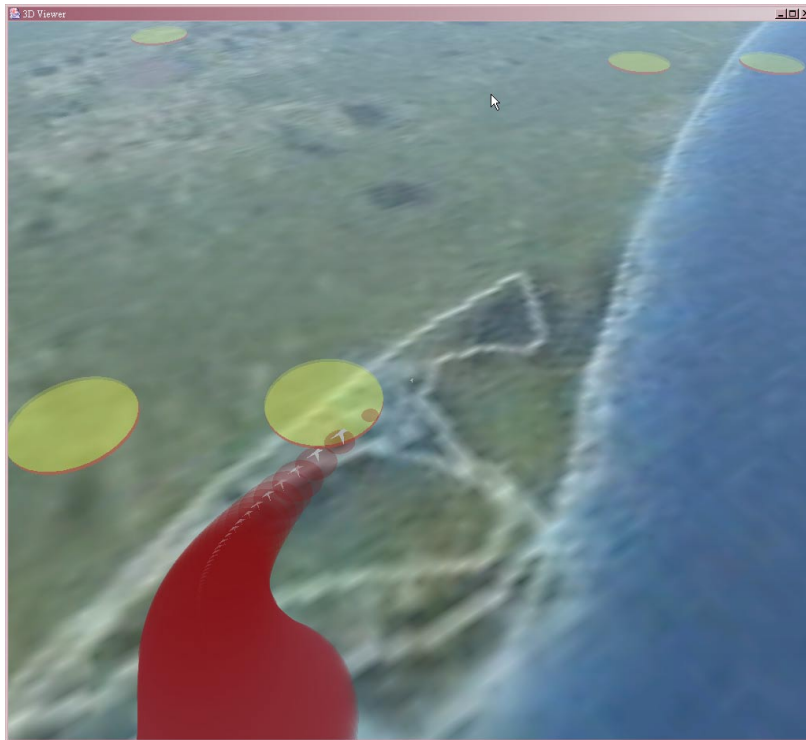
- Display of debris distribution at any time  $t$  resulting from vehicle breakup at time  $t_0$ , denoted  $D(t_0, t)$
- Display of composite debris distribution summarizing debris fallout history between breakup time  $t_0$  and current time  $t$ , denoted  $D(t_0, [t_0, t]) = \bigcup_{t_0 \leq \tau \leq t} D(t_0, \tau)$
- Display of composite debris distribution at current time  $t$  resulting from fallout due to all possible breakup of space vehicle since launch time  $t_L$ , denoted  $D([t_L, t], t) = \bigcup_{t_L \leq \tau \leq t} D(\tau, t)$

As Part 420 does not include modeling of the breakup itself, the debris field is modeled as a point at the initial breakup points, and increases in size as it descends. Hence  $D(t_0, t)$  behaves like an expanding circular disk as  $t$  increases. On the other hand, the debris model in Part 417 is more interesting, and  $D(t_0, t)$  may be composed of multiple debris volumes, possibly disconnected, resulting from the different fragment classes.

The display of  $D(t_0, [t_0, t])$  simply represents the composite debris effect due to a single point of breakup, whereas  $D([t_L, t], t)$  defines the totality at time  $t$  of the volume that may be affected by the space operation and any potential mishap along the way. In other words, the 3D volume as a function of time defines a 4D hypervolume which, if void of air traffic and population, would guarantee safety of the air traffic and population regardless of whether a mishap would occur. Figure 9 contains an example of the potential debris volume  $D([t_L, t], t)$  determined according to the formulation in Part 420. The disks represent an aircraft's 5-nmi horizontal separation minimum and its 1000-ft vertical separation minimum.

### Concluding Remarks

There exist a variety of launch vehicle developments funded both by public and private concerns to address future space-launch needs. Many of these concepts, particularly reusable launch vehicles (RLV), pose issues due to the



**Figure 9. Example 3D Visualization of Aircraft Separation Minimums and Potential Debris Fields**

possibility of their operations to and from spaceports away from traditional launch sites, possibly requiring supersonic flight over populated areas. The Air and Space Traffic Interaction Research (ASTIR) program seeks to develop analysis capabilities for studying the practicality of these concepts with respect to their implications on the air traffic in the National Airspace System (NAS) and the populated areas.

ASTIR builds on the Future ATM Concepts Evaluation Tool (FACET) developed by NASA. FACET contains powerful capabilities for studying the effect of advanced technologies on the full air traffic in the NAS. It supports realistic analyses through its ability to access live traffic data from the Host Computer or the Enhanced Traffic Management System (ETMS). ASTIR augments FACET with enhancements to enable it for studying space-operation in the NAS. The enhanced version of FACET — named Configurable Airspace Research and Analysis Tool (CARAT) to distinguish it from its precursor — contains new modeling capabilities for the space vehicles and reserved airspace, as well as new quantitative and qualitative analysis functionality.

The software and model-database designs provide flexibility to easily add vehicle models in the future, including automatic handling of space-vehicle staging events. The analysis functions support the study of interaction between air and space traffic, including the use of reserved airspace and the effect of potential debris fallout from space-vehicle breakup on the air traffic and populated areas. The 3D graphics capability enables qualitative visualization of these effects in an animated manner.

The CARAT functions discussed in the paper represents work in progress. The final product is expected to be applicable to pre-launch analyses including those required for licensing launch sites and individual launches. It can also be used in tradeoff studies to optimize launch operations with regard to their relationship with the air traffic. The tool is also useful to air traffic service providers to help them anticipate potential problems on the air traffic caused by scheduled space operations.

### **Acknowledgment**

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