Flight Safety Analysis Tool for Space Vehicle Operations in the National Airspace

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ABSTRACT

The military, civilian and commercial demands on space access are expected to experience a continuing increase. The many potential applications have been greeted by a plethora of new launch vehicle concepts with promises to enable more launches with reduced cost and improved reliability. The expectation that some reusable launch vehicles can operate to and from regular runways suggests the possibility of having spaceports conveniently located over the continental US. However, the prospects of allocating reserved airspace to support the increasing frequency of launches will likely be unwelcome to the air transportation community. Furthermore, the relatively lower reliability of space transportation vehicles compared to that of air transportation vehicles means that their operational requirements will need to look beyond normal operations to account for their impact on the air traffic and ground populations. An analysis tool has been developed to facilitate the study of new launch vehicle concepts and new spaceport locations in terms of their impact on the air traffic and ground populations. The tool has potential applications in spaceport planning, launch licensing, and mission planning. It will allow air traffic control to anticipate the impact of space transportation operations on the air traffic, using data made available close to the launch or return time windows. It will also enable launch operators to monitor space launch and return operations with visualization of the real-time air traffic, and perform post-operation or post-accident analyses.

INTRODUCTION

The different emphases in space access due to commercial, scientific research, and military requirements appear to have brought about successive changes in directions related to space launch vehicle programs in the last decade. In anticipation of telecommunications growth involving satellite systems, numerous government programs as well as "start-up" private ventures emerged to explore lower-cost alternatives to the existing launch-vehicle systems. Due to program cost overrun and the recent economic downturn, many of these programs have been terminated or gone through program adjustments. The evolution of these programs is ongoing [1] and much has changed even in the last few years [2]. The X-33 was a notable program with support from NASA to develop single-stage-to-orbit (SSTO) reusable launch vehicle (RLV) technologies, but was terminated by NASA in March 2001 [3]. Besides the need of launch technologies to support commercial applications, NASA also has specific needs for new launch capabilities to replace the aging Space Shuttle fleet for support of International Space Station (ISS) operations, and to support Earth Science and Space Science missions. In addition, the Department of Defense (DoD) doctrine in network-centric warfare is increasingly dependent on space-based capabilities to support command, control, communications, computer, intelligence, surveillance and reconnaissance (C^4ISR). Consequently, even when some of the commercial ventures in telecommunications are suffering temporary setback, the increasing trend of space-launch needs is continuing, albeit at a slower rate of increase than what was envisioned a few years ago.

Along with the fluctuating predictions of air launch needs, government agencies and private industry are continuously adapting their programs to address resource limitations and new requirements. The volatility in launch-vehicle technology goals is partly reflected in NASA's successive program definitions, beginning with the RLV Program that started the X-33 development in 1996, through the Space Transportation Architecture Study (STAS) in 1998, the Integrated Space Transportation Plan (ISTP) [4] including the Space Launch Initiative (SLI) [5] in 2001, to the latest Next Generation Launch Technology (NGLT) [6] and Orbital Space Plane (OSP) programs in 2003 [7]. The different government-supported programs and privately

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funded ventures produce a relatively broad spectrum of launch vehicle concepts ranging from expendable launch vehicles (ELVs) with traditional launch characteristics to advanced RLV concepts that can take off and land on standard runways. As a result, in addition to an anticipated increase in launch rate, the numerous concepts introduce new launch and return characteristics that may impose different operational requirements on the airspace. It has been suggested that if a launch vehicle can operate from and to regular runways, it would be able to operate like a regular airplane, including operation over land.

Mixing space launch vehicles with traditional air traffic is not trivial. Operationally, launch vehicles involve supersonic flight at altitudes occupied by commercial aircraft and hence they would require special handling. As far as safety is concerned, launch vehicles do not and are not expected to have the same level of reliability as commercial aircraft; furthermore, ELVs involve planned ejection of stage components, which will travel through the airspace as they descend to the surface. Consequently, launch vehicle operations will require safety analysis involving potential or planned debris. Current launch operations are separated from the air traffic through the use of Special Use Airspace (SUA). With the anticipated increase in launch operations, commercial users of the airspace may find the increased use of SUA objectionable, especially if it means that commercial space launches are viewed as given an unfair privilege for priority use of the airspace and allowed to interrupt the air traffic. Less interruptive airspace definitions and procedures are being explored to reduce the impact, with the FAA Space and Air Traffic Management System (SATMS) leading the effort [8–10].

For safety reasons, design of the special airspace and procedures needs to address debris effects due to potential staging or breakup of the launch vehicles. Existing launch licensing requirements concentrate on the launch phase, with little attention given to return flights of RLVs. The Columbia accident on February 1, 2003 suggests that these rules may need to be revisited as the breakup of the orbiter left a trail of debris over a large stretch of land including populated areas.

This paper reports on the development of an advanced flight safety analysis tool for studying the safety of space launch/return operations and their relationship with the air traffic. This *Configurable Airspace Research and Analysis Tool* (CARAT) enhances the air traffic simulation provided by NASA's *Future ATM Concepts Evaluation Tool* (FACET) [11, 12] with new functionality including the flexibility to set up new launch vehicle models. It includes flight safety analysis capabilities developed according to proposed FAA rules for launch licensing to determine hazard areas associated with space launches [13–15]. These capabilities will be instrumental for assessing the interruption of space launch operations on the air traffic, as well as casualty consideration related to ground population.

OVERVIEW OF CARAT

The *Configurable Airspace Research and Analysis Tool* (CARAT) builds on the *Future ATM Concepts Evaluation Tool* (FACET) developed at NASA Ames Research Center by augmenting it with additional functionality, including enhancements to make it more easily configurable by the user. Specifically, it allows the user to configure the FACET environment with new vehicle models and airspace configuration definitions. Additional functions enable the use of the augmented FACET for studying the impact of space launch and return vehicles on the air traffic in the National Airspace System (NAS).

Figure 1 illustrates the functional components of CARAT. CARAT supplements the original FACET program with four additional components. These include three components to support quantitative analyses in ASTIR — Space Vehicle Models, Special Airspace Definitions, and Flight Safety Analyses — as well as a 3-dimensional (3D) graphical capability to support qualitative visualization of the airspace and traffic interaction. These functions are described in more details in the following sections, followed by some evaluation examples of the tool.

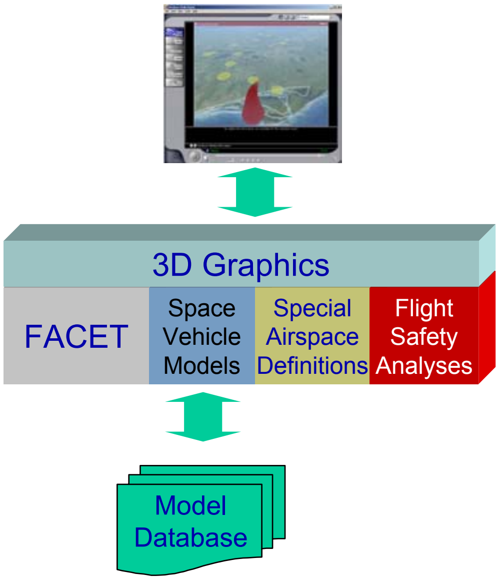


Figure 1. Functional Components of Configurable Airspace Research and Analysis Tool (CARAT)

SPACE-VEHICLE MODELS

Operation of the Space Shuttle, which is widely recognized as the 1st-generation RLV, is becoming so expensive that it is limited mostly to building and supporting the ISS. It is therefore natural to look to new launch vehicle technologies to provide more economical launches and enhanced capabilities. The 1994 National Space Transportation Policy led to the creation of the DoD Evolved Expendable Launch Vehicle (EELV) Program and the NASA RLV Program [16]. The 1996 National Space Policy identified NASA as the lead agency for research and development in civil space activities, and reinforced its commitment to develop a next-generation RLV. However, budgetary constraints have prohibited the full funding of the Space Shuttle, the ISS, as well as the full-scale development of an RLV. In 1996, the X-33 Project was initiated for demonstration with suborbital flights of technologies for a single-stage-to-orbit (SSTO) RLV, which would pave the way for the development of the VentureStar vehicle twice the size of the X-33 by Lockheed Martin, the X-33 contractor. The already slipping X-33 program, with its schedule further delayed by the 1999 composite-fuel-tank failure, was finally terminated in March 2001 when NASA let the cooperative agreement with Lockheed Martin expire. As NASA moves forward to re-evaluate its RLV strategy, other RLV technology demonstration programs have also been affected. The contract with Orbital Sciences Corp. on X-34 development was also terminated in March 2001. The USAF subsequently rejected the suggestion to pick up sponsorship of the X-33 and X-37 [3], where the latter was being developed by Boeing under contract to NASA.

As the NASA RLV program was experiencing its difficulties, the DoD EELV program was not without snags either. The rate of ELV losses in 1998–99 has cast doubt on the projected reliability of the EELV concepts, although the inaugural flights in 2002 of the two EELVs —Boeing's Delta IV and the Lockheed Martin's Atlas V — serve as a milestone to affirm the viability of the US ELV industry. 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 a focus on RLV systems based on two-stage-to-orbit (TSTO) concepts to lessen the demand on risky technologies, at the cost of an additional mating operation compared to X-33's SSTO concept. In the fall of 1999, NASA developed the Integrated Space Transportation Plan (ISTP) [4] with help from industry and academia to lay down the road map for near-term Space Shuttle enhancement and far-term RLV development. A central component of the ISTP was the Space Launch Initiative (SLI) [5], which included a 2nd-Generation RLV Program with the goal of substantially reducing the technical and business risks associated with developing safe, affordable, and reliable RLVs. The idea was that the 2nd-generation RLV would be developed and owned by private industry, of which NASA and DoD would be customers for launch services. Several of the privately funded ventures for RLV development [2] had responded to the SLI for funding, especially since none of them had thus far been financially viable with purely private funding. Examples of the private ventures in RLV development include the Kistler Aerospace Corp. K-1 vehicle [17] that uses conventional rocket propulsion and parachutes/airbags for landing as shown in Figure 2, and the Kelly Space and Technology, Inc. tow-launched RLV concept as shown in Figure 3.

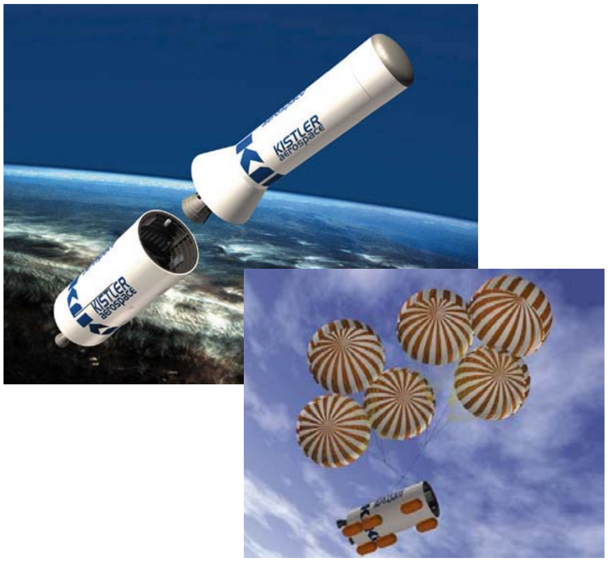


Figure 2. Launch and Return Concept of Kistler K-1

Major aerospace contractors including Boeing, Lockheed, and a team involving Northrop Grumman and Orbital Sciences, have played the prominent role in recent SLI concept development. Their concepts all show multiple stages of reusable vehicles, many of which depend completely on rocket propulsion. Figure 4 shows one of the 15 concepts generated by these contractors. Although the concepts presumably would use relatively mature technologies when compared to the X-33, many of these concepts would still require development of new major vehicle systems. Early in 2003, the SLI has evolved to serve as the theme for two emerging programs: the Orbital Space Plane (OSP) [7] and Next Generation Launch Technology (NGLT) programs. Four groups of concepts are being considered for the physical design of the OSP: (i) capsule, (ii) lifting body (iii) sharp body with wings, and (iv) blunt body with wings.

Figure 3. Kelly RLV Concept Involving Two Tow-Launched Returnable Vehicles

Besides focusing on the EELV program for heavy launch technologies, the DoD is anticipating a need to launch small payloads in short notice. The recent war experiences have evidenced the benefits of such a capability in support of various doctrines such as C^4ISR, network-centric warfare and battle damage assessment. Towards this goal the Defense Advanced Research Projects Agency (DARPA) selected six companies in 2002 [18] to develop designs for the Responsive Access, Small Cargo, and Affordable Launch (RASCAL) program [19]. The approach taken by RASCAL to provide a responsive, low-cost, and routine access to space for small payloads is based on a combination of reusable and expendable vehicles: a reusable aircraft first stage capable of exo-atmospheric, and low-cost expendable upper stages. The goal is to be able to deliver 50 kg of payload to low-Earth orbit (LEO) anytime at a high flight rate, to any inclination. Figure 5 illustrates the concept of operation envisioned for the RASCAL launches.

In addition to the RLV and EELV programs, the X PRIZE® Foundation is an educational nonprofit organization founded in 1995 for stimulating the creation of a new generation of launch vehicles designed to carry passengers into space. The X PRIZE is structured as an international competition that will award a $10 million cash prize to the first private team who safely launches and lands a vehicle capable of transporting three people on two consecutive suborbital flights to 100-km altitude within two weeks. A notable example of the entries is the Tier One Program under which Scaled Composites had been developing the vehicles under secrecy until their unveiling on April 18, 2003. It consists of a mother ship, the White Knight, which would carry the SpaceShipOne rocket glider to nearly 50,000 ft to initiate an air launch. A captive-carry flight test was performed on May 20, 2003, with the sortie clearing the envelope of expected altitude and airspeed for the joined pair, and going beyond the expected drop speed of 110 kn at 50,000 ft [20].

One of 15 industry concepts. (Boeing)

Figure 4. SLI RLV Concept Example from Boeing

Vehicle Model Database

The variety of launch and return vehicles 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. The model library initially implemented in CARAT consists of only generic models, which are not intended to be evaluation models for any specific concept in service or under development. Specifically, there are three generic launch vehicle models and four generic return vehicle models. The three generic launch vehicle models are:

- Vertical launch, single stage to orbit — This model is motivated by the X-33/VentureStar concept. It originated as a space-vehicle model obtained from the X-33 research team at NASA Ames Research Center. Since the X-33 was a half-size prototype vehicle for testing VentureStar technologies, the X-33 model was scaled up to twice its original size by the Ames researchers to facilitate our launch-vehicle and return-vehicle studies.
- Vertical launch, multiple stages to orbit — This model is motivated by the Kistler K-1 concept, which is relatively mature among the various RLV concepts pursued by private industry. This concept employs parachute and airbag for return. However, due to its use of conventional propulsion technologies, its launch characteristics are similar to those of conventional ELVs, and thus the model can be easily adapted to study ELVs including

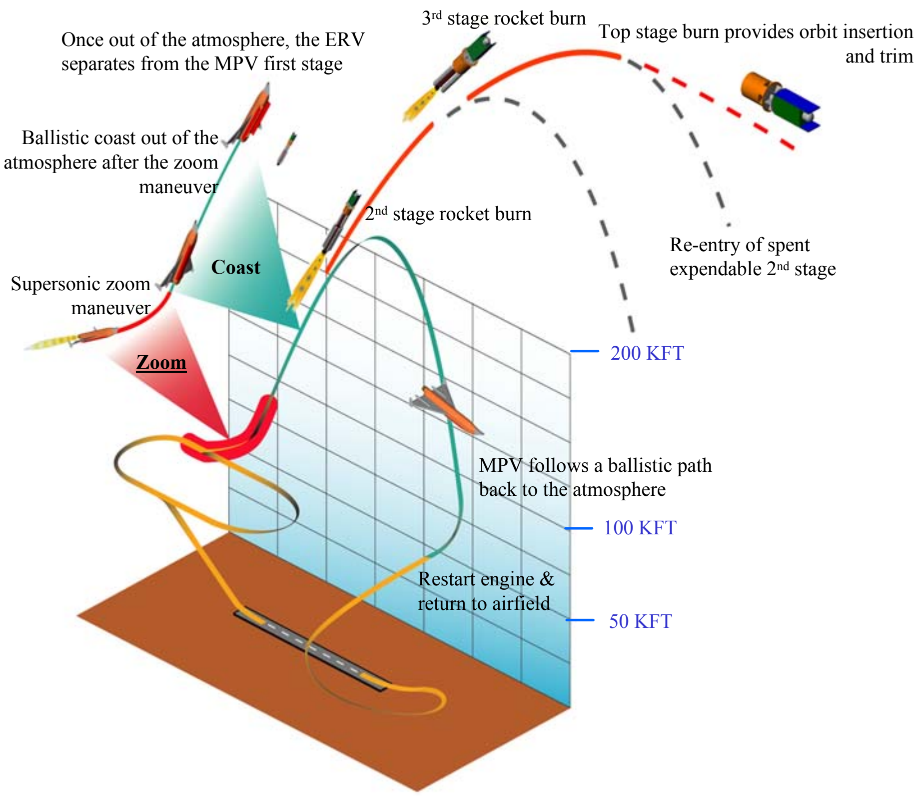


Figure 5. RASCAL Concept of Operation

EELVs, as well as several of the new SLI concepts with launch characteristics resembling those of conventional staged vehicles.

- Horizontal launch, aircraft air-breathing stage and rocket stages — Due to the similarity between runway-launch and air-launch concepts, this model encompasses and can be adaptable to both of these types of launch vehicles. This model includes a conventional aircraft first stage, which, depending on the concept, will either fly back after launching the subsequent stage or transition into a space plane to continue the launch into space. The second and subsequent stages of this model are rocket propelled, although the propulsion model can be adapted to include hypersonic air-breathing propulsion and hybrid designs.

The four generic return vehicle models are:

- Ballistic — This represents conventional expandable vehicle return without any mechanism to recover the vehicle or reduce the impact of the event. This is typical of conventional rocket stages that fall back into the ocean or land within a region cleared for the impact.
- Parachute — This model represents RLV concepts such as the Kistler K-1 and conventional unguided recoverable vehicle, including the return capsules commonly used prior to the Space Shuttle era.
- Unpowered glide — This model is typical for concepts such as the Space Shuttle and the X-33/VentureStar. Most of these vehicles have blunt-body designs to reduce heat protection requirements at re-entry, combined with lifting-body aerodynamics to enable the return flight for landing. The vehicles tend to have high drag performances and require landing operations to be uninterrupted. With new materials being researched to withstand higher temperatures at re-entry, the shape of future vehicles may allow better aerodynamic performance to leave more room for controlling the vehicles back to landing.
- Powered — This class of envisioned RLVs will likely have re-entry characteristics similar to the unpowered vehicles. Consequently at high altitudes they may go through similar deceleration with no propulsive power. They differ from their unpowered counterparts by allowing flight in the lower atmosphere to resemble that of conventional aircraft, allowing them to merge into regular air traffic for landing.

Most of these models involve combinations of separate individual models to represent the different stage configurations. Although the models are motivated by existing or proposed concepts, it should be emphasized that none of the vehicle models have been developed to evaluate any of the actual vehicle concepts. The aerodynamic and propulsion parameters are derived based on published information on the concepts. For instance, the aerodynamic data for some of the models have been generated using the AFRL Missile DATCOM program [21], with dimension and propulsion characteristics inferred from representative concepts. Moreover, a generic aircraft model is used to represent runway- or air-launch configurations in the subsonic regime, and to represent return vehicles flying back under power for runway landing.

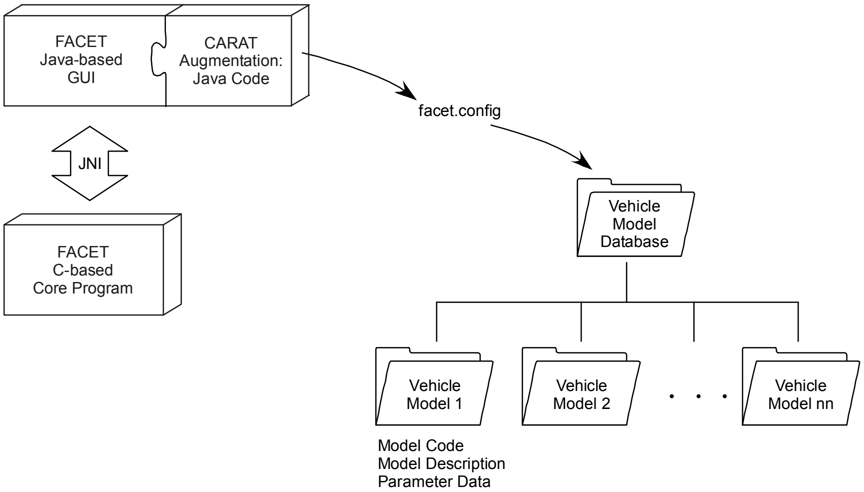


Figure 6. CARAT Augmentation of FACET for Configuring Vehicle Models

The software architecture in Figure 6 illustrates how FACET is augmented to accommodate new user-defined vehicle models without the need to update the FACET code every time a new vehicle model is introduced or an existing one is modified. The original FACET program consists of two pieces: a Java-based graphical user interface (GUI) serving as the front end, and a C-based core program serving as the backbone. The two pieces are represented by the two left-most blocks in Figure 6, and the communication between them is based on Java Native Interface (JNI). The CARAT augmentation consists of Java code that is directly integrated with the Java component of FACET. New vehicle models are implemented in Java and compiled into standard class files, which are deposited in an external vehicle model database that groups the models in a standardized directory structure.

Each vehicle model is stored in a separate directory, which contains the model code library for the model, as well as other files that describe the model and the pertinent parameters for configuring the model. When a user chooses to add a “CARAT aircraft,” CARAT automatically scans the model database to dynamically update the FACET menu with all vehicle models available for selection. Once a vehicle model is selected, CARAT retrieves the model information and constructs the GUI for the user to configure the vehicle model. When the user issues the command to run the simulation, the C simulation engine in FACET continues to maintain and update the aircraft states for the air traffic, but the simulation loop is intercepted by CARAT to allow the “CARAT aircraft,” i.e., user-selected launch vehicle models, to maintain and update their own state information.

Most of the new RLV concepts involve multiple stages. 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 instantiates the two model objects representing the vehicles after staging. The states of the two new vehicle models are derived automatically based on state of the pre-staging vehicle.

Augmented-FACET User Interface

FACET with the integrated CARAT enhancements contains a new “CARAT” pull-down menu that allows the user to configure CARAT options, bring up the 3D graphics display, and add custom aircraft models to the simulation. With the new aerospace vehicle models stored in the model database structure of Figure 6, bringing the mouse over the “Launch CARAT Aircraft” menu item triggers the program to scan the model database for new model types. CARAT processes all of the model types and displays a dynamic menu list containing all of the models currently available. Figure 7 contains an example illustrating the CARAT enhancement of the FACET GUI that includes the new menu item “Launch CARAT Aircraft”. The cascaded menu contains the different vehicle models that CARAT dynamically infers from the model database at run time.

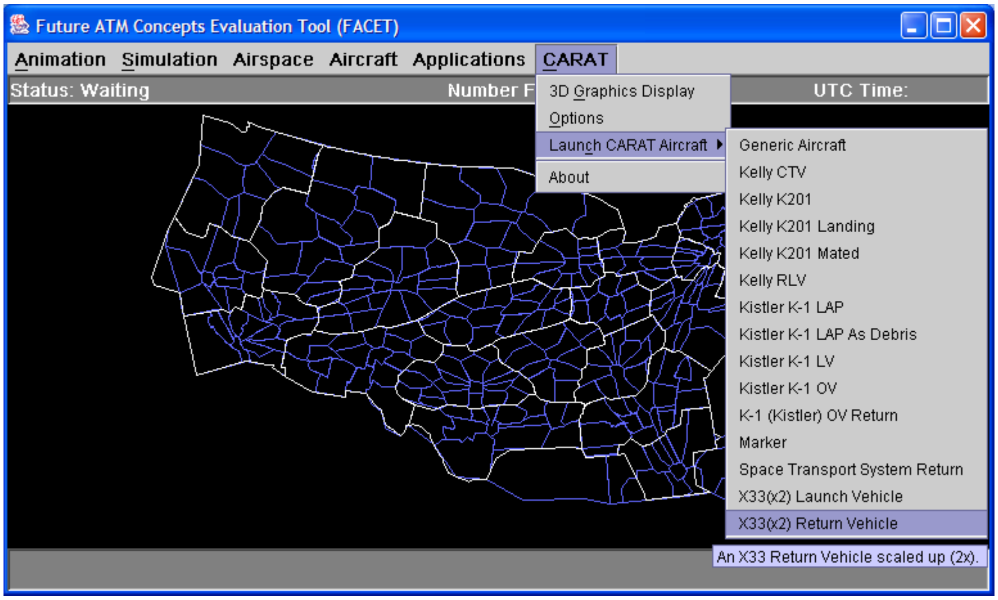


Figure 7. FACET GUI with CARAT Menu Generated at Run Time to Handle Custom Model Types

Once the user selects a model to be created, CARAT would retrieve the parameter data for the model from the database (Figure 6) and create a dialog window for adjusting the model parameters.

AIRSPACE MODELING FUNCTIONALITY

In current space launch or return operations, Special-Use Airspaces (SUAs) are defined to keep the air traffic away from potential hazards due to the operations. In consideration of future air transportation needs, the FAA has been studying new traffic management tools and procedures, including dynamic configuration of airspace within and between facilities, to deliver operational flexibility, workload management, and better contingency handling [22].

Special Airspace Definitions

The FAA SATMS program considers further changes in airspace philosophy and structures to address space transportation needs [8–10, 23]. First, an upper limit of the NAS is specified to demarcate the FAA's operational responsibilities. The FAA provides traffic flow management and separation assurance to vehicles and they transition through the NAS to and from this upper limit of the airspace. Within this NAS demarcation, two new airspace structures are proposed to manage space vehicle operations:

- *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.

Figure 8 illustrates the possible use of STC and flexible spaceway for launch operations of different types of launch vehicles, whereas similar definitions of STC and flexible spaceway can be defined for return operations of these vehicles [2].

Since the modeling of these new airspace structures is similar to that of SUAs, except for smaller extents in time and space, the SUA functionality provided by FACET is adequate for their modeling and analyses, and no major augmentation is required from CARAT.

Debris Modeling

As space transportation vehicles do not deliver the same level of reliability as commercial aircraft, it is necessary to define hazardous regions in the airspace caused by potential debris from space transportation operations. The extent of the potential debris needs to account for both operational failures and planned ejections. The FAA rules for licensing a lunch site [13] and the proposed rules for licensing individual launches [14, 15] contain debris-modeling requirements with various levels of details. CARAT includes functionality compatible with these requirements for predicting the debris dispersion, which can be used in the definition of hazard volumes as functions of time.

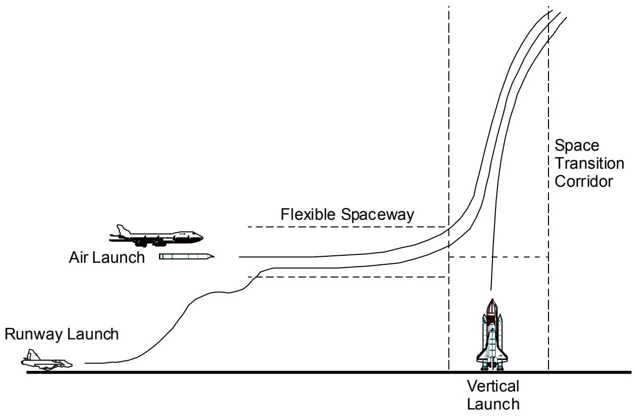
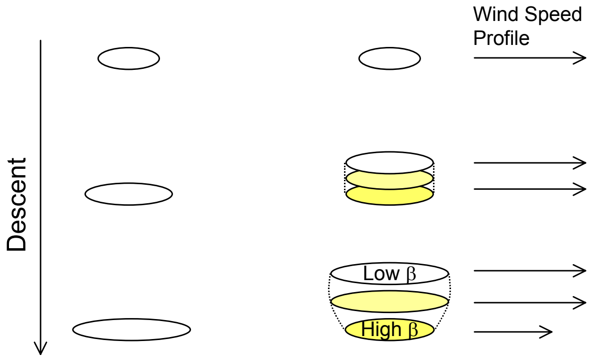


Figure 8. Illustration of Airspace Definitions with Different Launch Concepts

The FAA regulations for launch-site licensing described in 14 CFR Part 420 [13] require the verification that the site can support at least one type of launch operation that will satisfy the requirements, which include an upper bound on expected casualty (E_C) of 30×10^{-6} per launch. The requirements involve the determination of the flight corridor based on debris dispersion resulting from launch vehicle failure. The procedure for propagating the debris dispersion is based on statistical wind data containing only wind speed information, but lacking wind direction specificity. Figure 9(a) illustrates how the debris uncertainty propagates as it descends through the atmosphere.



(a) Single β (b) Multiple β

Figure 9. Effect of Omni-Directional Statistical Wind on Debris Dispersion

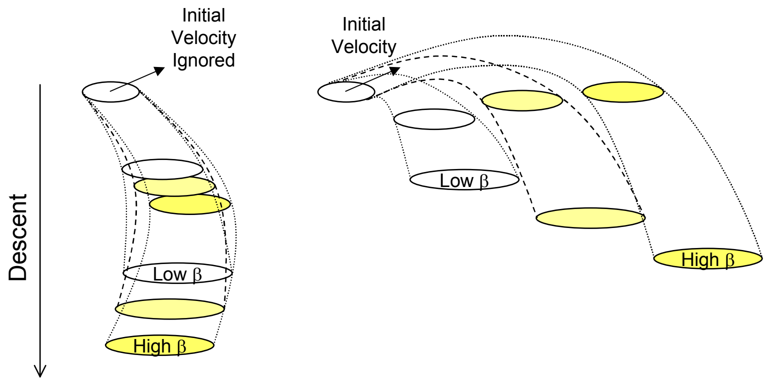
CARAT can be further enhanced by considering various parts of the debris according to the distribution of the ballistic coefficients. Since an object with a higher ballistic coefficient β has a higher terminal velocity than a low-β one, the high-β debris would descend faster than the low-β debris. When the wind field is constant, the uncertainty is identical between the different debris fields at the same time instant, even though the high-β field would fall faster than the low-β field. As illustrated in Figure 9(b), as the high-β field transitions to an altitude of different wind speed, its dispersion would start to deviate from the rest. The aggregate debris field can be approximated by the envelope of the individual fields corresponding to the range of β values. As the debris reaches the ground, the high-β field should be contained within the low-β field. This is consistent with the common observation that the lighter debris is generally blown farther away than the heavier debris, when effect due to the initial velocity is ignored.

On the other hand, the proposed rules for individual-launch licensing described in 14 CFR Part 417 [14, 15] require more specific analyses. The statistical wind data used by the procedure therein for determining debris dispersions require finer granularity in altitude levels, and the data contain both wind speed and direction information [24]. Figure 10(a) illustrates the steady-state effect of the statistical wind vector on the debris dispersion.

It is already obvious that the debris dispersion model in Figure 10(a) is more realistic than the one in Figure 9(b). However, this more-accurate model still does not take into account the velocity of the vehicle at the initial breakup point. When considering breakup events at high altitudes and high speeds, such as the Columbia accident on February 1, 2003, the transient effect of the air drag simply cannot be ignored. To this end, the model is extended to account for the air drag caused by the speed of the debris relative to the wind. Figure 10(b) illustrates the transient effect of the debris dispersion.

Dynamic Hazard Volume

The previous section describes several ways that the debris dispersion due to a vehicle breakup or ejection can be modeled. Regardless of which dispersion formulation is used, let $D(t_0,t)$ denote the hazard debris uncertainty field at time t caused by the vehicle breaking up at t_0, i.e., a flight outside of $D(t_0,t)$ would be in no danger of being hit by any debris at time t due to a breakup at time t_0. The set $\{D(t_0,t)|t \geq t_0\}$ defines the dispersion history due to the vehicle breaking up at



(a) Steady-State Effects (b) Transient Effects

Figure 10. Effect of Statistical Wind Vector on Debris Dispersion

t_0, and it can be used to compose the debris history volume corresponding to the breakup.

For the purpose of planning air traffic routes around potential launch vehicle debris, vehicle breakup is not known a priori. It would be beneficial to be able to group together all the potential debris to form a debris volume for the air traffic to avoid as a function of time. This set is defined as $\{D(\tau,t)|t_L \le \tau \le t\}$ where t_L is the launch time. This Dynamic Hazard Volume (DHV) represents all the potential debris dispersions at time t from all possible breakups since the launch at time t_L. In other words, if the air traffic is kept away from this DHV, then safety from any potential debris is assured.

ANALYSIS TOOLS

CARAT provides a set of analysis tools useful for studying the interaction between space operations and the air traffic, and for support of trade-off studies of air-traffic-control and space-operation options, with safety of the air and space transportation vehicles being a major consideration. FACET as an analysis tool when augmented with space-vehicle models already provides a rich set of functionality that is useful towards analyses of the interaction between the air and space traffics in the NAS. FACET supports these analyses through its capabilities in determining vehicle trajectories and analyses tied to the definition of SUA. The trajectories can be used in studying separation requirements, while the combined use of the trajectories with the definition of special airspace structures can support the following analyses:

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

The rules proposed in 14 CFR Part 417 for licensing of a specific launch include numerous analyses related to the air traffic in the NAS. The following is a list of the relevant analyses:

- Trajectory Analysis — to establish the nominal trajectory of the launch and possible uncertainties due to wind and performance errors. CARAT allows the user to perform the various trajectory analyses through user-supplied input parameters and control algorithms.
- Malfunction Turn Analysis — to determine the greatest turning capability as a function of time. The analysis results can be used as input to flight safety-limit analysis and other analyses to determine how far a launch vehicle's impact point can deviate from the nominal impact point when a malfunction occurs. CARAT allows the user to simulate the malfunction turns by providing the necessary model and conditions.
- Debris Analysis — to identify inert, explosive, and other hazardous debris resulting from a malfunction of the launch vehicle or any planned jettison of launch-vehicle components. CARAT is designed to accept the result data from the debris analysis and use them to compute the effects of debris dispersion. The initial CARAT implementation can handle debris classes defined according to fragment ballistic coefficients, covering inert and explosive fragment types and jettisoned components.
- Flight Control Lines Analysis — to define the geographic region for permitted flight and debris impact. The analysis will identify the region in which a launch vehicle is allowed to fly, and where debris resulting from normal flights and any malfunction will be allowed to impact. CARAT's graphics capabilities can be used to show the flight control lines to support visualization of the regions during the other analyses.
- Flight Safety Limits Analysis — to determine the criteria for terminating a malfunctioning launch vehicle's flight, so that any resulting debris dispersion will stay within the flight control lines. The simulation capability of the CARAT system is useful for computing the nominal and malfunction trajectories, which can be used for the flight safety limits analysis. The graphics capability of CARAT allows the user to visualize the resulting data.

- Wind Analyses — to determine the wind magnitude and direction as a function of altitude for the airspace through which the launch vehicle will fly and for the airspace through which malfunctioned and jettisoned debris will travel. CARAT has been designed to allow user input of the wind data to support the other analyses.
- Flight Hazard Areas Analysis — to determine the regions of land, sea, and air exposed to potential adverse effects of planned and unplanned lunch vehicle flight events, which must be monitored, controlled, or evacuated in order to ensure public safety. CARAT has been developed to account for the debris dispersion effect, which can be used to help compute the flight hazard areas. Due to the air-traffic-oriented nature of this project, the development of CARAT has initially focused on the flight hazard area for aircraft hit. The graphics capability of CARAT can be used for visualization of this volume, which should cover the airspace below 60,000 ft. The debris impact hazard area on land is related to the individual-hit contour, which also requires post-simulation processing. The capability to determine the flight hazard area for ships can be developed as an extension of the aircraft-hit contour.
- Debris Risk Analysis — to determine expected casualties (E_C) to the collective members of the public exposed to inert and explosive debris hazards from the proposed flight of a launch vehicle. The debris dispersion model in CARAT is useful towards the debris risk analysis. Instead of computing E_C, the individual-hit contour discussed below is identified in Part 417 as a related analysis topic that is based on the same debris requirements and failure probability, but it does not depend on population data as the computation of E_C does.

Some of these analyses such as the definition of flight hazard areas are directly affected by the presence of air traffic, while others such as trajectory analysis and debris analysis are required for providing the necessary data to support these analyses. Two analyses selected for detailed implementation in CARAT involve post-simulation processing: aircraft-hit contour and individual-hit contour. These are part of the flight hazard area analyses.

Aircraft Hazard Area

Due to the historically lower reliability of launch vehicles relative to that of traditional aircraft, an important consideration is the debris resulting from planned or unplanned breakup of the launch vehicle. The effect of the debris defines an aircraft hazard area, where the probability of an aircraft within this hazard area being struck by debris would exceed a predefined, acceptable level. Determination of this aircraft hazard area is the "air" component of the Flight Hazard Area Analysis. The aircraft hazard area ensures that the probability of an aircraft being hit by the debris is $\leq 10^{-8}$, and it is obtained through the determination of an aircraft-hit contour corresponding to a debris class. The debris data and wind data are provided by the launch operator. The rules in 14 CFR Part 417 provide the implementation requirements for computing the aircraft-hit contour as the result of a falling stage or ejected debris. Per Part 417 requirements, the aircraft-hit contours are computed for altitudes between 60,000 ft and the surface.

Individual-Casualty Contour Analysis

In addition to its impact on the air traffic, potential debris from launch vehicles also need to account for potential casualty on the ground population. There are two functions considered as requirements related to ground population casualties. The first is the commonly cited requirement of expected casualty $E_C \leq 30 \times 10^{-6}$ along the launch corridor. The Debris Risk Analysis for this requirement needs to consider the population data [25] along the flight corridor to determine E_C. This analysis is not included in the CARAT functionality, but can be included in the future if the need arises and resources are available. The second function is a proposed FAA rule that the individual-casualty probability P_C would not exceed 10^{-6} for a launch. This can be accomplished by ensuring that there is no human presence within the individual-casualty contour corresponding to $P_C = 10^{-6}$.

Implementations of the aircraft-hit contour and the individual-casualty contour in CARAT are both described in detail in the Air and Space Traffic Interaction Research (ASTIR) final report [26].

GRAPHICAL USER INTERFACE

In addition to the enhancements introduced by CARAT to the FACET graphical user interface to support the introduction of new vehicle models into the FACET simulation as described above, CARAT augments FACET with 3D graphics to support the display of traffic, debris dispersion, and post-simulation analysis visualization.

Since the graphical front-end of FACET is developed in Java, it does not have extensive 3D graphics functionality. CARAT adds such functionality through the use of OpenGL, which is a popular standard for 3D computer graphics. To interface the Java code to an OpenGL library, which usually provides interface functions compatible with standard C calls, "OpenGL for Java" has been selected to provide the bindings between the Java and C standards. OpenGL for Java is available under the GNU Library General Public License (LGPL). Figure 11 illustrates the architectural relationship between the FACET code and OpenGL through the use of OpenGL for Java.

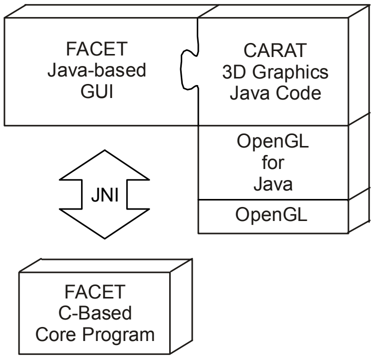


Figure 11. CARAT Augmentation of FACET for Enabling 3D Graphical Display

The 3D display functions of CARAT are summarized in Figure 12. Figure 13 shows the primary 3D graphics window of CARAT. The terrain elevation data is obtained from the National Imagery and Mapping Agency (NIMA). The current data set is from NIMA's Digital Terrain Elevation Data (DTED) Level-0 product. The texture map for the terrain graphics is obtained from the map imagery made available by National Geographic.

CARAT provides three display modes for showing the debris dispersion. The most generic display mode is Elements, which renders the individual debris class dispersions as individual ellipses. When there are more than one instance of a debris class dispersion present, as in the case when simulating breakups at multiple time instances, the user may select Tunnel or Wireframe as the visualization method. In either of these modes, all elliptical debris dispersion elements of the same class are connected, resulting in a rendered "tunnel" for each debris class. In multiple breakup scenarios, these tunnels together constitute the Dynamic Hazard Volume introduced above. The tunnel mode uses 3D solid modeling for display the tunnel, while the wireframe mode, as its name implies, displays the tunnel using 3D vectors to define the connected surface.

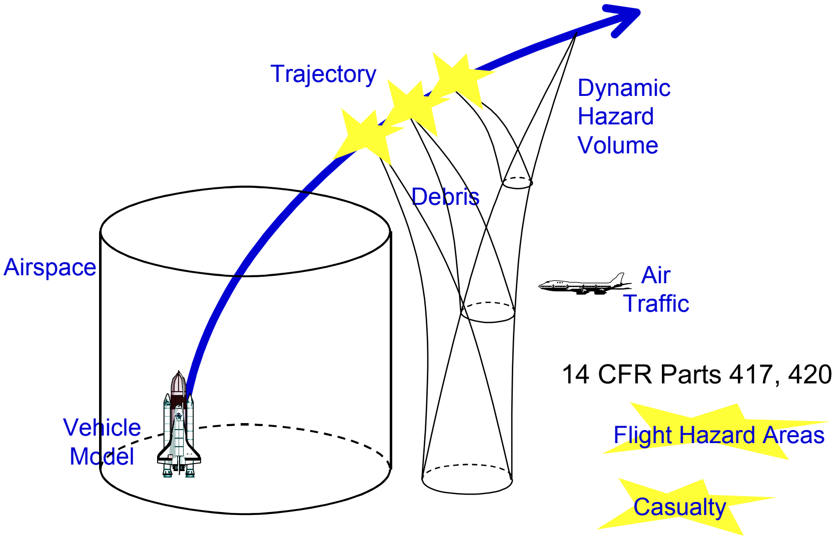


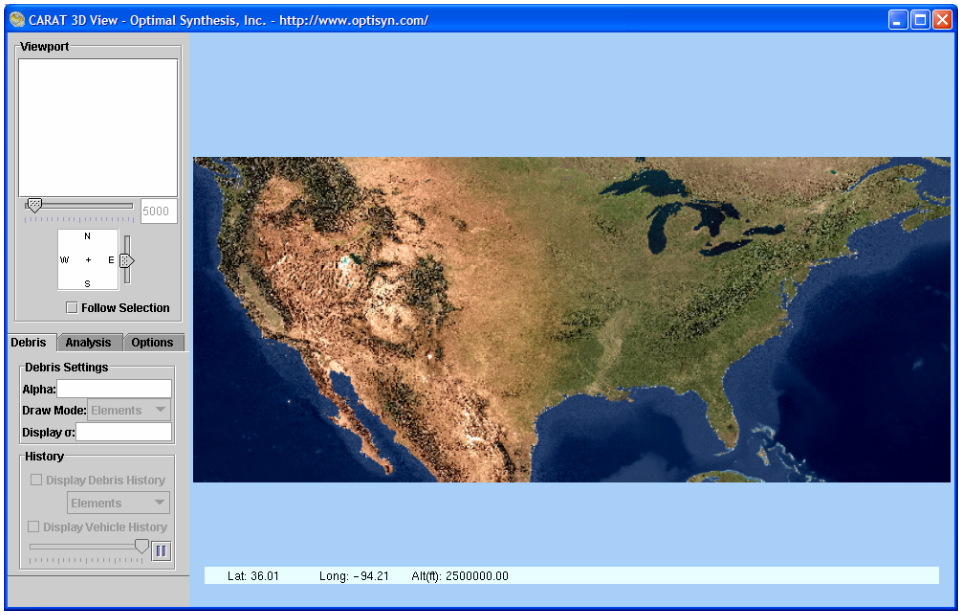
Figure 12. CARAT Functions Benefiting from 3D Graphical Display

EVALUATION EXAMPLES

The 3D graphics window mirrors the display of aircraft on the FACET display as shown in Figure 14, while providing the user with an unlimited number of angles with which to view the traditional air traffic. The FACET 2D display uses triangular icons to indicate the positions of the aircraft. On the CARAT 3D display, aircraft are displayed using cylinders centered about the aircraft's position. These cylinders by default are drawn with a 5-mile diameter and 1000-foot height to represent the separation requirements. In other words, if the cylinders of two aircraft come into contact, the aircraft are in violation of the separation requirements. Each cylinder also contains a triangle indicating the current heading of the aircraft.

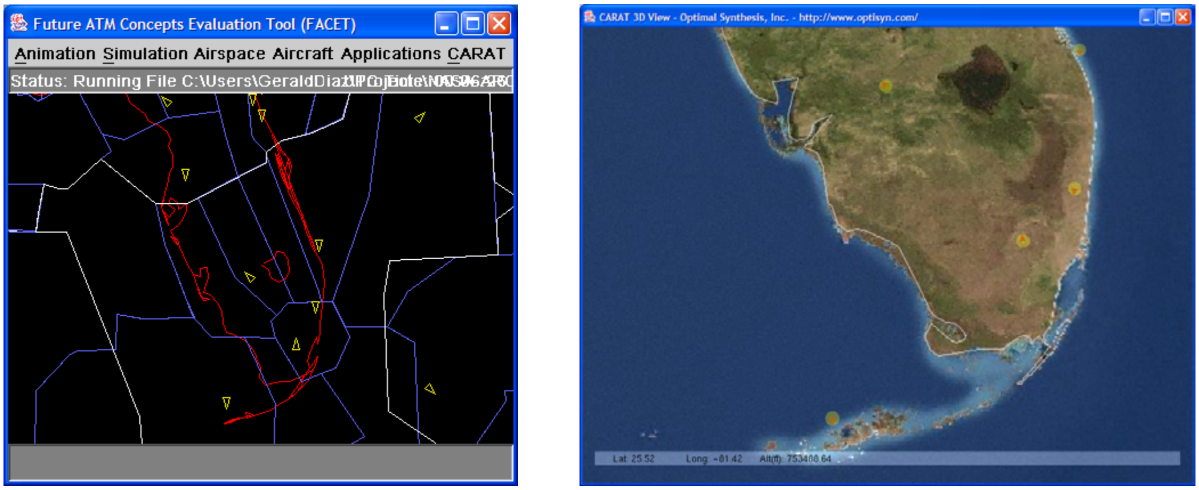
CARAT provides the flexibility for the user to associate any user-provided 3D graphical model with the vehicle model. The user provides this by extending the vehicle class with the appropriate OpenGL software and graphical data, and including the model data in the database. Figure 15 illustrates a few vehicle graphical models rendered by CARAT using this capability.

Motivated by the Columbia accident on February 1, 2003, an example has been created to illustrate how the debris analysis capabilities of CARAT can be used to predict and visualize the debris dispersion resulting from breakup of a Space Shuttle during its return trip. Figure 16 illustrates the debris dispersion histories of different debris classes resulting from a single breakup along the Space Shuttle's return path. Since



Lat: 36.01 Long: -94.21 Alt(ft): 2500000.00

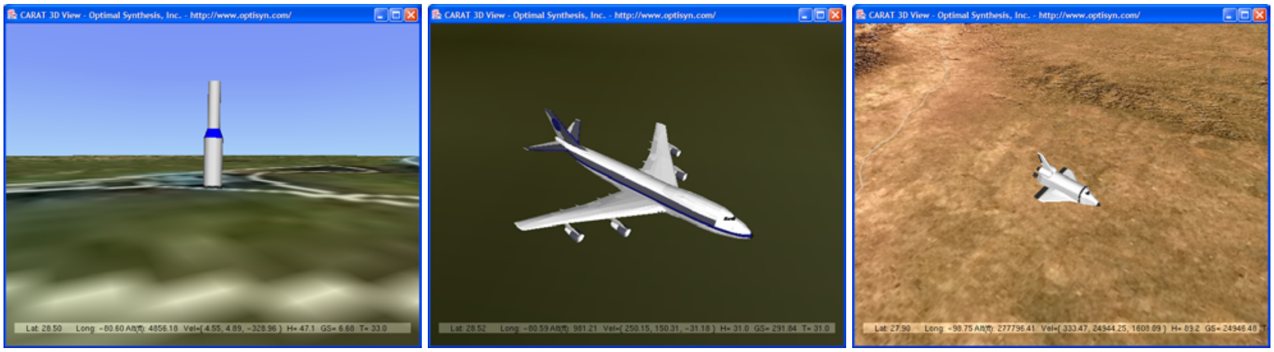
Figure 13. CARAT 3D Graphics Window



Status: Running File C:\Users\GeraldDiaz\Projects\NASA-ARC

Lat: 25.52 Long: -81.42 Alt(ft): 753408.64

Figure 14. Parallel 2D and 3D Displays of Air Traffic



Lat: 28.50 Long: -80.60 Alt(ft): 4856.18 Vel=(4.55, 4.89, -328.96) H= 47.1 GS= 6.68 T= 33.0

Lat: 28.52 Long: -80.59 Alt(ft): 981.21 Vel=(250.15, 150.31, -31.18) H= 31.0 GS= 291.84 T= 31.0

Lat: 27.90 Long: -98.75 Alt(ft): 277796.41 Vel=(333.47, 24944.25, 1608.09) H= 89.2 GS= 24946.48

Figure 15. CARAT Flexibility for User to Provide 3D Graphical Model of Vehicles

during re-entry the Space Shuttle is flying at hypersonic speeds and at high altitudes where the air density is low, it is imperative that the debris dispersion model takes into account the transient effects as discussed earlier.

The next example is motivated by the SSTO concept involving the X-33(2×) model. Figure 17 shows the wireframe display of the DHV extending down to the surface during the vehicle's ascent.

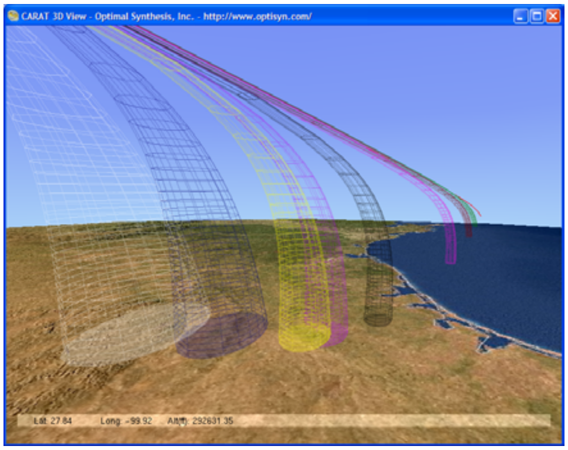


Figure 16. Illustration of Debris Dispersion Histories Resulting from Simulated Breakup of Space Shuttle

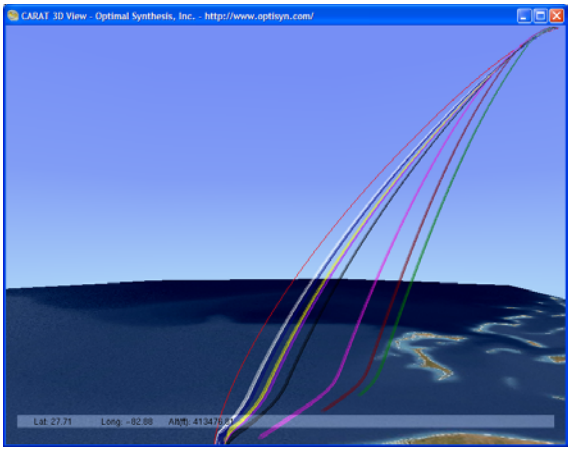


Figure 17. Display of Dynamic Hazard Volume for Launch Flight of X-33(2×)

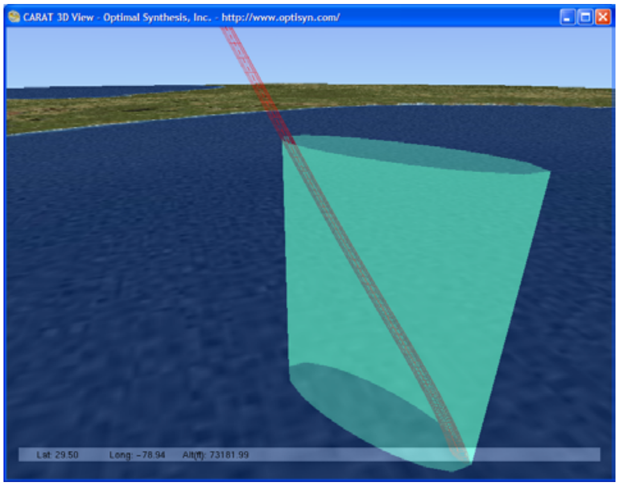


Figure 18. Flight Hazard Area Around Aircraft-Hit Contours from 60,000 ft Down to the Surface

Demonstration of the Aircraft-Hit Contour computation is provided using an example resembling an ELV with the first stage simulated as an ejected component falling as a piece of debris. Figure 18 shows the Aircraft-Hit Contours as the debris descend to the surface, and the resulting Flight Hazard Area constructed automatically after the simulation to enclose the aircraft-hit contours between the 60,000-ft ceiling and the surface. This volume is specified using the SUA function of FACET.

The final example demonstrates the Individual-Casualty Contour using an example motivated by the Kistler K-1 Launch Vehicle, with the launch operation continuing with the return of the first stage to base. The contour probability is based on a threshold value of 10^{-6}, and a probability of breakup of 10^{-4} per sec along the launch flight trajectory. Note that this relatively large probability of failure is chosen to show a more pronounced Individual-Casualty Contour. The resulting contour in Figure 19 illustrates the different effects that the wind has on the dispersion of the difference debris classes.

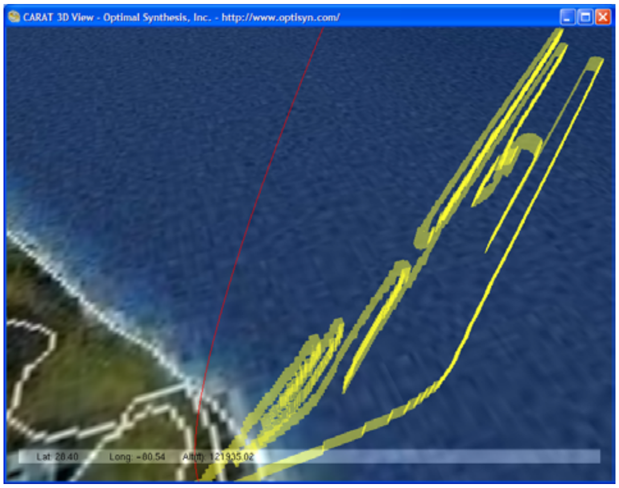


Figure 19. Individual-Casualty Contour for Simulated First Stage Returning to Base

CONCLUDING REMARKS

The Future ATM Concepts Evaluation Tool (FACET) developed at NASA Ames Research Center provides an extensive set of modeling, simulation and analysis capabilities for studying air transportation in the National Airspace System. By adding space transportation vehicle modeling, the Configurable Airspace Research and Analysis Tool (CARAT) reported herein builds on the FACET capabilities to produce an environment that is effective for studying the interaction between the space and air traffics.

CARAT introduces a flexible vehicle-model database that allows the user to easily add and configure air and space transportation vehicle models for integration with the FACET simulation. The database enables dynamic reconfiguration of FACET's Java-based graphical user interface to reflect user addition or modification of the models. Vehicle models, their characteristics and 3-dimensional (3D) graphical visualization models can all be dynamically added to the model database without further need to modify the FACET program.

Most of the new airspace structures being considered to support air transportation operations with reduced use of reserved airspace and time can already be modeled using the Special Use Airspace (SUA) functions available in FACET. CARAT adapts these SUA functions to model such proposed airspace structures as Space Transition Corridors and Flexible Spaceways. Observing the need of space transportation systems to address planned staging events and unexpected mishaps, the development of CARAT uses FAA-proposed requirements for debris analysis to model potential debris dispersions associated with space transportation operations. In particular, CARAT has introduced the definition of Dynamic Hazard Volume to represent the time-varying region of the airspace that would account for all the debris dispersion, making it possible to plan routes for the air traffic with assured clearance from danger caused by the space transportation vehicle, be it planned or unexpected.

The vehicle simulation and debris dispersion propagation together support the development of several flight safety analysis capabilities. Two of the more comprehensive capabilities involve post-simulation processing to generate the aircraft-hit contour and the individual-casualty contour. These analyses are useful for defining the flight hazard areas for the air traffic and on the surface.

CARAT provides 3D graphics capabilities based on solid modeling for visualization of the terrain, vehicles, their potential debris dispersions, and special airspace structures. These visualization capabilities enhance the other analysis functions.

Various stakeholders can benefit from CARAT as a planning and analysis tool. Spaceport planning organizations can use CARAT to help define locations for constructing spaceports to reflect the required operations, with due regard given to the surrounding communities, populations, and air traffic. CARAT can also help with the licensing of the launch site. Launch operators can use CARAT to plan for launches and perform the analyses required for licensing. The FAA, as the agency responsible for licensing commercial launches, can use CARAT to perform independent analyses to verify the launch operators' claims. NASA and the Department of Defense can use CARAT to perform similar analyses to support non-commercial launches.

Up to the time of the actual operation, the launch operator, range control, and air traffic control can use CARAT to rehearse the launch or return operation. CARAT can also provide real-time visualization during the operation. The fact that FACET and CARAT can mix simulation data and surveillance/telemetry data means that CARAT is suitable for post-operation analyses, irrespective of whether the operation has been successful or resulted in failure.

ACKNOWLEDGMENT

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