Integration of Reusable Launch Vehicles into Air Traffic Management

Phase I Final Report

NEXTOR Research Report RR-97-7

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Preface

This report documents research undertaken by the National Center of Excellence for Aviation Operations Research, under Federal Aviation Administration Research Grant Number 96-C-001. This document has not been reviewed by the Federal Aviation Administration (FAA). Any opinions expressed herein do not necessarily reflect those of the FAA or the U.S. Department of Transportation.

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Executive Summary

Separation between air traffic and space vehicles has traditionally been performed through the activation of large regions of Special Use Airspace (SUA) that prohibit entry of aircraft not involved in launch or reentry operations. Space launch and reentry operations, especially those of Reusable Launch Vehicles (RLVs), will become more common and more widespread. Some space activities may include air-launched assets (e.g., Pegasus) that operate as conventional aircraft during takeoff and landing and could be based at conventional airports rather than at specialized facilities. Additionally, flexible procedures are needed in the event that an RLV suffers a malfunction during launch, on-orbit, or reentry, necessitating rapid reintroduction into the air traffic system. New sensor, communications, and human interface technologies can now provide the means by which more efficient and complex modes of operation can be used. It is therefore necessary to reexamine the procedures through which air traffic is separated from RLV traffic.

To begin to address these issues, Massachusetts Institute of Technology (MIT) and Virginia Tech (VT) undertook a Phase I study as part of the National Center of Excellence for Aviation Operations Research (NEXTOR), from April through September, 1997. The goal of this study was to identify the critical issues that need to be addressed and the tools that could be used to address them. MIT focused on RLV mission profiles and modes of utilizing airspace, and VPI focused on identifying models and methods to quantify and optimize costs of RLV operations in the National Airspace System (NAS).

Because of its operational simplicity, it is recommended that SUA should generally be used unless a significant negative impact on air traffic is identified. SUA is relatively simple to activate, and procedures can be developed by ATC to reroute traffic. SUA also provides a large degree of safety and the most flexibility for the space operation when compared to other concepts that have been identified. Several technological and human-factors issues will be examined in Phase II of this project to determine the requirements for and costs of the equipage that would be required for more integrated use of the airspace. At the same time all important RLV operational modes will be analyzed to quantify costs to users, service providers and non-airspace users.

The Phase I research has also identified models and methods to quantify costs of RLV operations in NAS. The approach devised consists of two models: 1) a cost model to determine the economic impact of using SUA (i.e., implementing flight trajectory diversions) and 2) an optimization model to minimize the impact of RLV operations through a reconfiguration of flight schedules. Progress has been made in the development of these two models and they have been tested with simple airspace scenarios to verify the approach taken.

1.0 Introduction

Space exploration is entering a new phase with the development of technologies enabling space launcher reusability beyond that achieved by the current U.S. Space Transportation System (STS). Coupled with increased demand for commercial utilization of space, Reusable Launch Vehicle (RLV) operations are expected to become more common within a few years, once the basic technologies are proven and deployed. With the increase in operations, the airspace usage during launches and recoveries can be expected to increase. To date, private enterprise in the operational space launch industry has been limited, but is expected to increase to beyond that by government agencies and the military. To ensure ‘fair use’ of airspace by all these entities and the air transportation industry, strategies for air and space traffic management need to be developed. At the same time, safety must be maintained.

Separation between air traffic and space vehicles has traditionally been performed through the activation of large regions of Special Use Airspace (SUA) that prohibit entry of aircraft not involved in launch or reentry operations. Because current space operations are relatively rare and occur at only a few localized sites in the world, activation of SUA has not caused large delays or workload in the air traffic system. However, space launch and reentry operations, especially those of RLVs, will become more common and more widespread. Some space activities may include air-launched assets (e.g., Pegasus) that operate as conventional aircraft during takeoff and landing and could be based at conventional airports rather than at specialized facilities. Additionally, flexible procedures are needed in the event that an RLV suffers a malfunction during launch, on-orbit, or reentry, necessitating rapid reintroduction into the air traffic system. New sensor, communications, and human interface technologies can now provide the means by which more efficient and complex modes of operation can be used. It is therefore necessary to reexamine the procedures through which air traffic is separated from RLV traffic.

Each potential procedure or mode of operating airspace carries with it certain requirements on technologies, equipage, and operator workload. These costs must be balanced against the potential economic benefits of improved traffic flow to determine whether a proposed concept is viable.

To begin to address these issues, Massachusetts Institute of Technology (MIT) and Virginia Tech (VPI) undertook a Phase I study as part of the National Center of Excellence for Aviation Operations Research (NEXTOR), from April through September, 1997. The goal of this study was to identify the critical issues that need to be addressed and the tools that could be used to address them. MIT focused on RLV mission profiles and modes of utilizing airspace, and VPI focused on identifying models and methods to quantify and optimize costs of RLV operations in the National Airspace System (NAS). The work will be extended to perform preliminary technical evaluations as Phase II. This report is divided into two major sections: Chapter 2 covers the MIT effort, and Chapter 3 describes the VPI effort.

2.0 Summary of the MIT Effort

2.1 Background

The current method by which space operations and aircraft operations are separated is through the definition of Special Use Airspace (SUA). SUA is depicted on aeronautical charts, and, when active, prohibits entry of aircraft not involved in the special operation. SUA intentionally provides an excess safety buffer in space and time to physically separate the different operations. Due to its size, activation of SUA can generate a negative impact on air traffic flow (e.g., the Kennedy Space Center SUA covers approximately 900 square miles).

As space operations become more common, frequent activation of SUA will begin to affect commercial air traffic to an extent that usage conflicts may arise between the parties involved. Given that the current mode of operation transfers a segment of airspace from being exclusively available to air traffic (when the SUA is inactive) to being exclusively available to space operations (when the SUA is active), it is desirable to examine the potential for integrating or mixing access to airspace during space operations. Adding to this potential are the facts that certain RLVs have phases of flight similar to conventional aircraft, and that advancing technologies may enable air traffic control to better monitor separation between vehicles.

Additionally, given that the future of the National Airspace System is currently under review through concepts such as free flight, it is appropriate that steps be taken to examine drivers from the space operation segment. Such consideration at this early stage may facilitate future airspace policy decisions.

2.1.1 Phase I Objectives

The objectives of the MIT segment of Phase I were to:

- Outline current methods of RLV-aircraft separation in use at the Special Use Airspace (SUA) areas around the US Launch Ranges (Cape Canaveral, Vandenberg AFB, and Wallops AFB)
- Outline mission profiles of the proposed RLVs and characteristics of the respective phases of flight
- Develop a generalized model of airspace / air traffic / RLV operations to provide a consistent framework to describe and evaluate options
- Define potential modes of operation / airspace utilization for RLV operations by understanding current requirements and procedures, and explore possible alternatives
- Provide recommendations for further study and implementation

The focus was on airspace shared with conventional aircraft (i.e., below 50,000 ft). Additional consideration will eventually be needed for the potential for RLV-RLV separation as well as for separation of conventional aircraft from Unmanned Aerial Vehicles or other specialized activities.

2.1.2 Primary Information Sources

The information contained in this report was principally obtained from the following sources (see also the Reference Section at the end of this report).

- Federal Aviation Administration
- NASA
  - Kennedy Space Center
  - Wallops Flight Facility
- Department of Defense
  - US Air Force: Patrick AFB, Andrews AFB
  - US Army
- Industry
  - United Space Alliance
  - Orbital Sciences Corp.
  - Kistler Aerospace
  - Pioneer
  - Roton
  - Lockheed-Martin

2.2 Model of Airspace Concepts For Space Operations

2.2.1 Methods of Traffic Separation

Airspace traffic separation is achieved in the National Airspace System by a number of control methods and procedures to provide adequate safety margins. Traffic separation rarely relies on a single method alone, as increased safety and robustness to failures are required. There is wide variation in the degree of control exercised from the ground, ranging from VFR aircraft that self separate visually, to IFR aircraft that are actively vectored. Whenever possible, control systems and procedures are layered to provide redundancy against failures (e.g., TCAS).

The primary separation methods can be subdivided according to whether the control is performed centrally (normally by ground ATC centers), or is distributed among the aircraft themselves. Once again, there normally is overlap between the control methods.

2.2.1.1 Centralized Control

Centralized control is what is normally thought of as ‘traditional’ air traffic control. The control center assumes primary responsibility for separation. Within centralized control areas, the airspace is classified according to the type of control that is exercised. Several methods may operate simultaneously:

- **Segregated airspace**

  Vehicle operations are restricted to predefined airspace regions (e.g., Special Use Airspace, flight levels, airways, etc.) that are either preassigned or communicated to the users while in operation. The assignment is made via regulations, charting, Notices to Airmen (NOTAMs), or Air Traffic Control. Separation is “built-in” apriori and the air traffic control task is the assignment of the allowable region to the user.

- **Active control (e.g., Class A-D airspace)**

  In regions such as terminal areas where segregated airspace is not practical, active control is used. A centralized traffic separation specialist monitors all vehicles in real time through radar or procedural separation methods and issues commands as needed. Generally, communications are required between ATC and the aircraft operating in actively controlled airspace.

- **Partial control (e.g., Class E airspace)**

  Partial control is used in areas where ATC can only monitor and/or control a subset of all vehicles using the airspace. This might be necessary where communication with all users is not guaranteed, as when IFR and VFR traffic is mixed. Controlled vehicles may be vectored around traffic, while the uncontrolled vehicles rely on self-separation.

2.2.1.2 Decentralized Control

In “Decentralized Control”, the users themselves achieve and monitor separation. It is used often in parallel with centralized control (e.g., TCAS). Decentralized control has smaller response times in general, as communications delays and other overheads are minimized. In addition, better local information may be available to the self-separating parties as compared to that available to the central controller due to sensor or processing limitations.

- **Self-separation**

  In VFR and some “free flight” concepts, the pilots themselves are responsible for detecting and resolving conflicts. “Rules-of-the-road” are in effect but may be limited. Increased pilot workload often results, as a higher degree of spatial situation awareness is required (“see and avoid”). Self-separation may result in sub-optimal flow or instabilities and higher uncertainties are present in future state predictions as multiple independent entities now share the separation responsibility as opposed to a single entity, as in centralized control.

- **Automated warning system**

  Automated threat warning and avoidance systems are often necessary as aids

> to the pilot for time-critical collision avoidance. Systems such as TCAS provide backup separation assurance in occasions when the centralized control fails to recognize the conflict early enough. Pilots are warned of the impending threat and respond to automated and possibly coordinated commands if both aircraft are similarly equipped to avoid collisions.

The use of centralized or decentralized control affects the time scales by which traffic conflicts are detected and resolved. As shown in Fig. 2-1, there is a range of these time scales. Centralized control tends to operate from the longer-term Tactical, Strategic or Preflight zones, while decentralized control operates more often at the time-critical or shorter-term tactical zones.

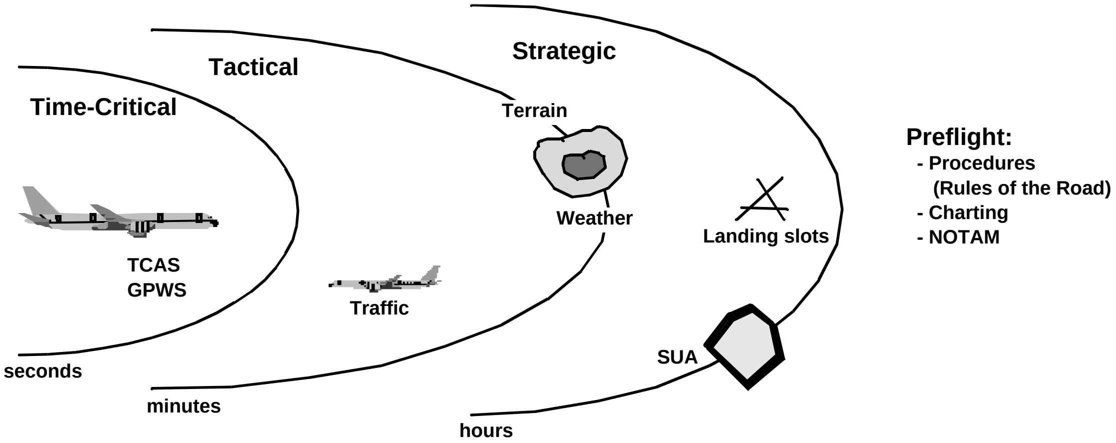

Figure 2-1: Hazard Mitigation Timeline
(Adapted from Sally Johnson, NASA Langley Research Center)

<u>2.2.2 Drivers of Airspace Concepts</u>

As Figure 2-2 shows, there are several competing demands placed on the choice of how airspace is defined and used. A given concept for airspace will impact both air traffic flow and the ability of RLV operations to be performed when needed. For example, activation of SUA restricts air traffic flow, but provides flexibility to the space operator. There may also be certain vehicle equipage requirements (e.g., transponder), and there may be ground infrastructure requirements (e.g., radar). Finally, a given concept may affect safety and operator workload (both for the pilot and ground controller).

Working to improve one of the issues in Fig. 2-2 alone may negatively impact the others. For example, increasing the safety buffer size of SUA will improve safety and RLV operational flexibility, but will negatively impact air traffic flow, and possibly controller workload due to increased needs to reroute traffic. Thus, each of the six considerations in Fig. 2-

2 were considered together when examining future airspace concepts.

2.2.3 Potential Information Flow in the Airspace System

The airspace system is composed of a number of entities which execute and control its use. Information can potentially flow between any of these entities (Figure 2-3). The mode of operation essentially determines communication and surveillance requirements. For example, under VFR self-separation, no communication with ATC is required, although the aircraft may be monitored by primary radar.

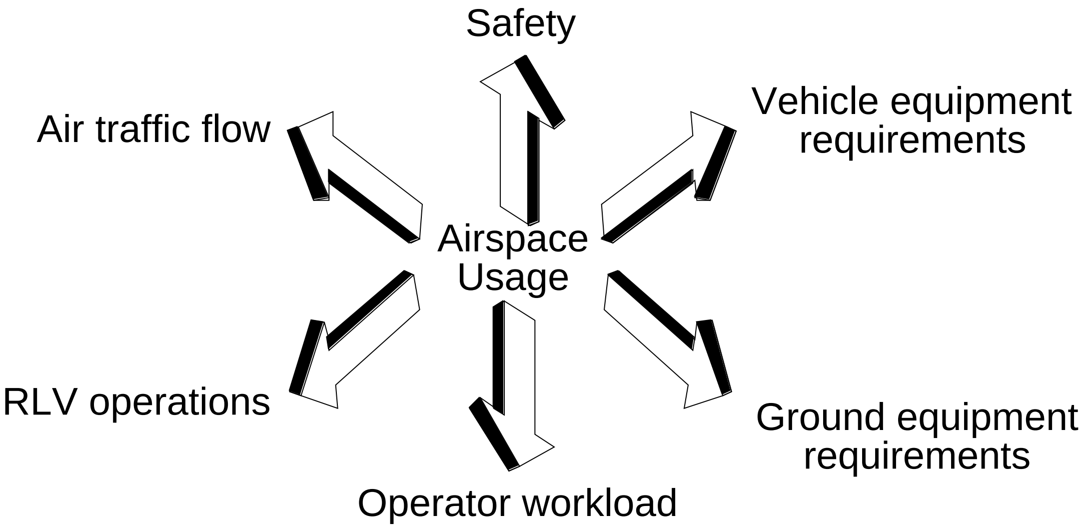

Figure 2-2: Airspace Usage Considerations

2.3 Current Methods of Aircraft - Space Operation Separation

The current methods for achieving separation between space and air operations rely on large static spatial and temporal buffers between the domains. Strategic space operation-aircraft separation is achieved through Special Use Airspace (SUA), similar to that used for military operations, around the eastern and western launch ranges and Wallops (Fig. 2-4). During operational periods, uninvolved air traffic is kept away by ATC and the launch site operators. SUA provides an excess safety buffer in space and time, to physically separate space operations from civilian airspace use. Typically, the airspace is active several hours before and after the space operations occur.

The special use airspace is activated during space operations, and ATC is informed and works air traffic around SUA (Figure 2-5). ATC may be able to observe the space vehicle through primary radar, while air traffic in the region is also observed by the RLV Operations Center (ROC). Should a violation occur, ROC directs chase aircraft to escort uncooperative or unresponsive aircraft out of the SUA.

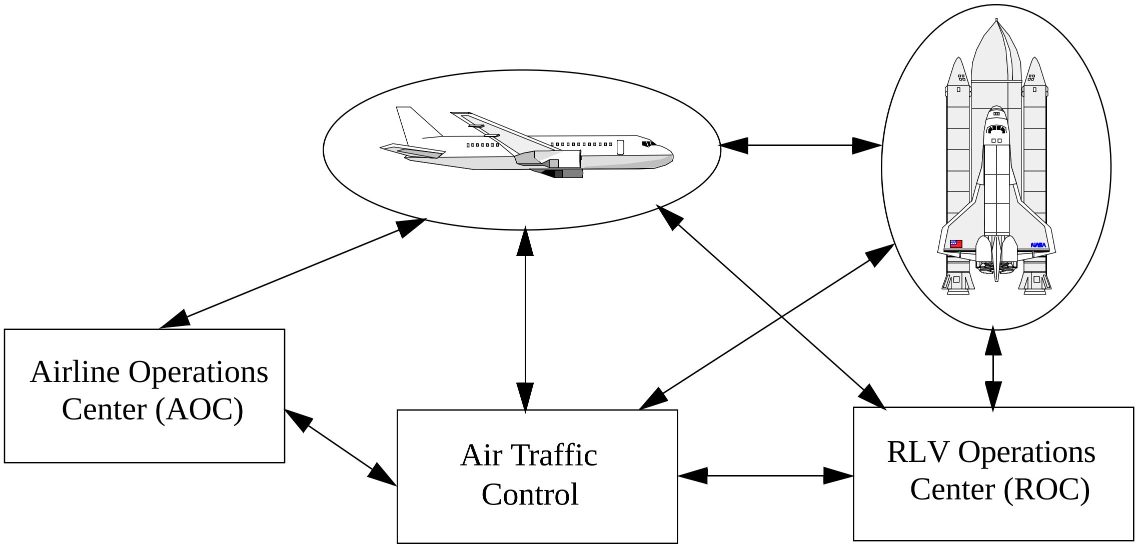

Figure 2-3: Potential Information Flow in the Airspace System

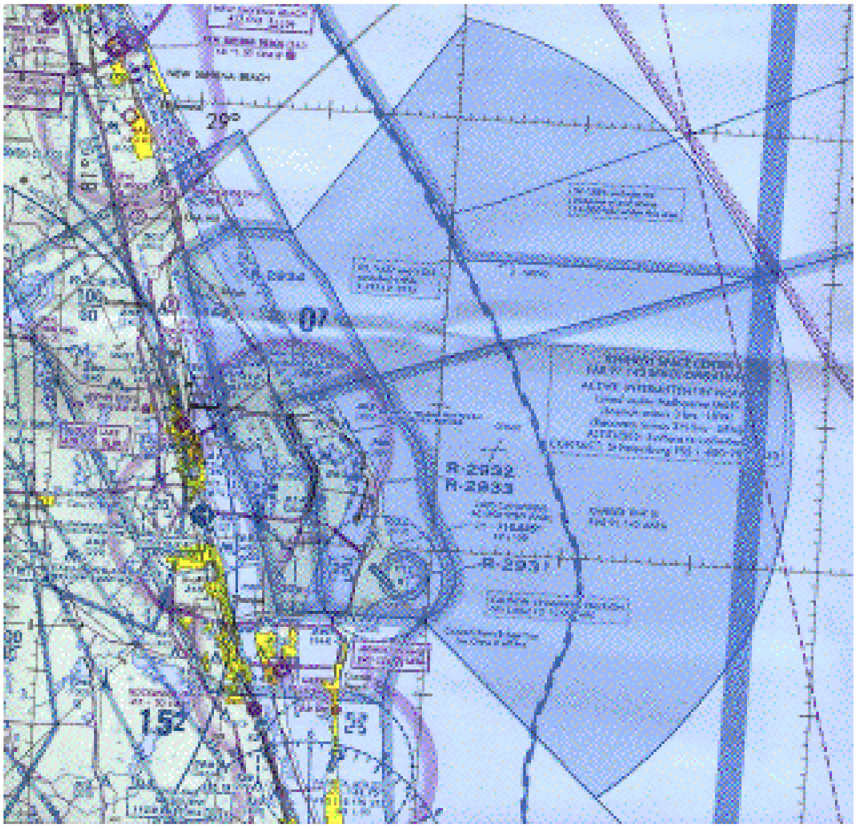

Figure 2-4: Kennedy Space Center Special Use Airspace (dark-tinted region) (Jacksonville VFR Sectional Chart)

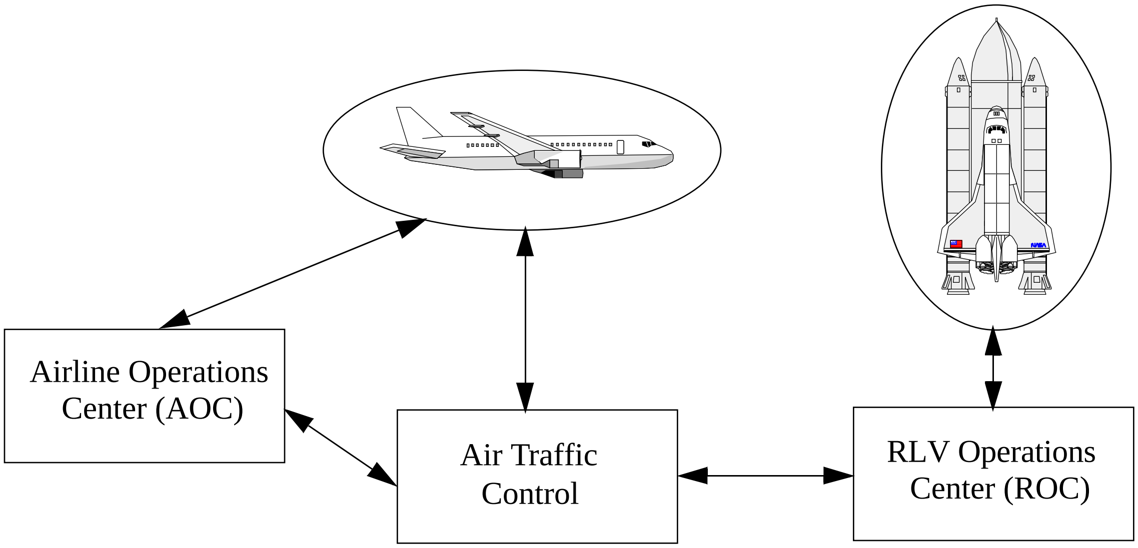

Figure 2-5: Information Flow in the Current Space SUA System

2.3.1 Alternate Types of Special Use Airspace (SUA)

The FAA defines several types of Special Use Airspace, listed below. Each type affects the priorities given to air traffic and to the user of the SUA.

1. Prohibited / Restricted Airspace (charted):
    - No entry by any uninvolved aircraft while active
    - Special use has priority over all other operations

2. Military Operations Area (MOA) (charted):
    - Entry of uninvolved aircraft is allowed while active
    - Military mission must monitor and avoid transiting aircraft
    - Mixed special and other aircraft use

3. Controlled Firing Zone (not charted):
    - Entry of uninvolved aircraft is allowed while active
    - Military activity must cease when aircraft is transiting
    - Other aircraft have priority

2.3.2 Current Space Operation SUA Definition Process

The current launch vehicle SUA definition process involves a detailed study of the launch system capabilities and risk factors. The size of the SUA is determined by limiting the probability that the vehicle crosses the boundary to outside airspace to 1 in 10 million. Potential impact points of released stores, or of a malfunctioning vehicle are estimated, and the mission is aborted, if possible, before crossing the boundary.

The timing of SUA operation is determined so that it is early enough for NOTAMs to be communicated at preflight, especially for VFR aircraft. In addition, auxiliary operations (e.g., atmospheric sounding) may also need to be performed before the actual mission starts. The SUA is typically activated about 3 hours before operation begins. Unnecessary activation sometimes occurs as the operation is canceled or delayed after the NOTAM is issued.

2.3.2.1 Launch Monitoring Requirements

Current space operators are required to fulfill Launch Monitoring Requirements. During any launch, an Instantaneous Impact Point (IIP) is continuously calculated assuming an instantaneous propulsion loss, and is displayed in real time to a controller on the launch monitoring consoles. The required IIP accuracy (3σ) is:

Along-track: < 100’ or 5% of range (whichever is larger)
Cross-track: < 100’ or 0.5% range (whichever is larger)

The IIP moves at very high speed (thousands of kilometers per second) late in the launch and the above standards are then relaxed.

The minimum required data telemetry update rate is 20 Hz, while the minimum IIP update rate is 10 Hz. Should the IIP cross outside of the abort boundary (which is based on safety studies), a self-destruct must be initiated and the maximum allowable destruct delay is 1.5 - 3.5 seconds. The minimum required tracking system reliability is 0.999 over 1 hour.

2.4 RLV Characteristics

Reusable launch vehicles generally possess performance characteristics different than conventional aircraft. In certain phases of flight and for certain RLVs, however, there may be similarities with conventional aircraft in terms of vehicle state and performance.

2.4.1 Proposed Space Vehicles

A survey of proposed space vehicles was performed to begin to determine potential mission types and phases of flight. Many RLV designs are in the concept and development stages. The major current and planned space vehicles are listed in table 2-1. A number of other studies not listed here are also underway. In the “Type” column in Table 2-1, VT and HT mean Horizontal and Vertical Takeoff, respectively; HL and VL mean Horizontal and Vertical Landing, respectively.

Table 2-1: Space Vehicle Types

Type	**Vehicle**	**Features**	**Service Date**
VT-expendable	Conventional	Current launchers (Titan, Atlas,...)	now
VT-expendable	EELV	Proposed ELV replacement	2000
VT-expendable	Sea Launch	Ocean launched Zenit	1998
VT-HL	Shuttle	Partially reusable	now
VT-HL	X-33	Test Vehicle	1998
VT-HL	Venture Star	SSTO, Potential Shuttle replacement	2003
VT-VL	DC-Y	DC-X follow-on	N/A
VT-VL	Kistler K-1	2 stages, parachute + airbag recovery	1999
VT-VL	X-37	Space Station Alpha crew return, ELV launched, parachute landing	2000
VT-VL	Roton	Rocket propeller	N/A
HT-HL	HOTOL	Study, Dormant	N/A
HT-HL	Pegasus	Air launched, expendable	now
HT-HL	Sänger	Study phase	N/A
HT-HL	X-34	Test vehicle, B-52/L-1011 launched	1998
HT-HL	Pioneer	Piloted, LOX refueled at altitude	1999
HT-HL	NASP	Study phase	N/A

2.4.2 Flight Phases

Any RLV mission can be subdivided into a number of flight phases (Figure 2-6). Multi-stage vehicles also have some phases occurring in parallel for boosted or jettisoned stages. The phases of flight are further defined in Table 2-2.

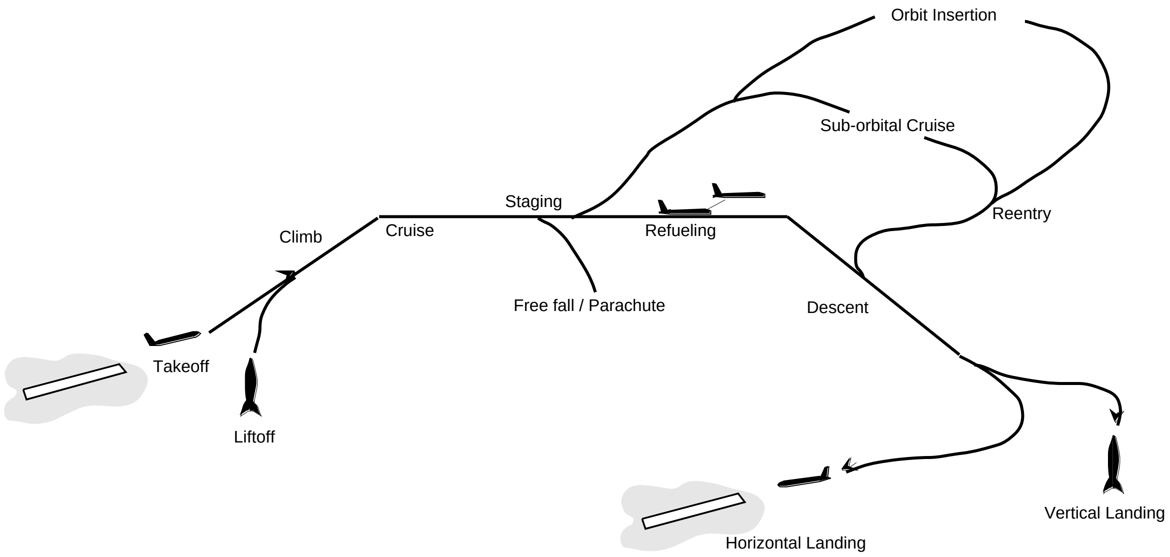

Figure 2-6: RLV Phases of Flight

2.4.3 Mission Profiles

Mission profiles can be derived from vehicle and mission-dependent combinations of flight phases. Table 2-3 shows the vehicle-flight phase relationships. The takeoff, climb, cruise, descent, and horizontal landing phases may be similar in form to conventional air operations. In many cases, however, there are extreme horizontal and vertical velocities and the vehicle may have extremely limited maneuverability; in such a case, it becomes difficult to combine RLV and air operations in the same airspace.

Table 2-2: RLV Flight Phases

Phase	Definition
Takeoff	Conventional, Aircraft-type horizontal launch on a runway
Liftoff	Rocket-type vertical launch from a launch pad
Climb	Flight with large positive vertical velocity component
Cruise	Flight at constant altitude / low vertical rate
Staging	Planned separation of vehicle components
Refueling	Transfer of fuel or oxidant from one flight vehicle to another
Sub-orbit Cruise	Free-fall trajectory of less than one orbit
Orbit Insertion	Boost to orbit / exit atmosphere
Re-entry	Into the atmosphere
Descent	Flight with large negative vertical velocity component
Horizontal landing	Conventional, aircraft-type horizontal recovery on a runway
Vertical landing	Near-vertical recovery (controlled and/or powered)

Table 2-3: Vehicle Mission Profiles

Vehicle	Takeoff	Liftoff	Climb	Cruise	Staging	Refueling	Sub-orbit	Orbit	Reentry	Descent	H Landing	V Landing
Conventional		x	x		x		x	x				
EELV		x	x		x		x	x				
Sea Launch		x	x		x		x	x				
Shuttle		x	x		x			x	x	x	x	
X-33		x	x				x		x	x	x	
Venture Star		x	x				x	x	x	x	x	
DC-Y		x	x				x	x	x	x		x
Kistler K-1		x	x		x		x	x	x	x		x
X-37		x	x		x			x	x	x		x
Roton		x	x				x	x	x	x		x
HOTOL	x		x	x	x		x	x	x	x	x	
Pegasus	x		x	x	x		x	x		x	x	
Sänger	x		x	x	x		x	x	x	x	x	
X-34	x		x	x	x		x		x	x	x	
Pioneer/Pathfinder	x		x	x	x	x	x	x	x	x	x	
NASP	x		x	x			x		x	x	x	

2.5 Potential Modes of Operation

Eight potential modes of using airspace for RLV operations were identified and are listed below. These modes are not meant to indicate an exhaustive list, but do provide a range of likely operating regimes.

- Use current spaceport SUA
- Create new spaceports / SUA
- Mission-specific SUA
- RLV-intensive airspace category
- Real-time RLV corridor
- RLV as high-priority vehicle
- RLV as nominal-priority vehicle
- Self-separation

Each mode is briefly discussed below, including its notional benefits and limitations. These notional ratings must be further defined, which is the focus of the Phase II effort.

2.5.1 Use Current Spaceport SUA

Current Spaceports (Cape Kennedy, Vandenberg AFB, Edwards AFB, White Sands AFB, and Wallops AFB) will continue to operate in the foreseeable future. The first option is to utilize these for all future RLV operations. Safety studies for new vehicle operations, to define any required modifications to the current SUA regions, can be performed and then charted.

During operation:
Space facility notifies FAA/ATC
NOTAMs are issued
Pilot obtains NOTAM, chart during preflight
In flight, ATC reroutes aircraft around SUA
Little or no communication is required between ATC and launch operator

> **Pros:** The SUA regions are already defined and modifications are expected to be minimal as the RLVs should be more controlled and reliable than current vehicles. The procedures are simple, because the traffic remains segregated, and safety is not reduced due to the large safety buffer.
>
> **Cons:** Blocking off large chunks of airspace has negative impact on air traffic. While the RLV operation may take only a few minutes to complete, the airspace remains blocked for hours to provide a large time buffer for VFR aircraft. Furthermore as the frequency of RLV operations rises, capacity limits may be encountered.

2.5.2 Certify New Spaceport SUA

Keeping the SUA definition philosophy intact, new RLV flight facilities are added as needed, in geographically suitable locations, to accommodate increased RLV operations.

> **Pros:** Can provide increased accessibility and capacity for RLV operations, while maintaining the benefits of current SUA.
>
> **Cons:** More restrictions on air traffic flow are added. Finding new geographical locations that satisfy land overflight and safety requirements while meeting mission requirements is a difficult problem.

2.5.3 Mission-Specific SUA

Current SUAs are designed to accommodate the entire range of space operations from a spaceport. Subsections of the SUA can be designed that satisfy the launch safety requirements for a subset of the possible launches. The appropriate sub-section of the SUA is then activated depending on the mission. Other procedures remain the same as for the typical SUA.

For example, at the Kennedy Space Center, the SUA extends from an azimuth of 35˚ to 135˚ over the Atlantic Ocean. However, space launches are allowed only between azimuths of 65˚ - 110˚. A high-inclination launch at 65˚ may not actually require that the entire SUA extend to 135˚. The potential therefore exists that the SUA could be subdivided and the subsections activated depending on the specific mission.

> **Pros:** Reduced impact on air traffic is expected, but may be inconsequential. The advantages of the typical SUA are retained.
>
> **Cons:** Charting difficulties may be encountered as the complexity increases and features such as overlaps are needed in SUA definitions. Increased potential for misunderstanding or miscommunication is also expected with the increase in communications between ROC, ATC, and aircraft.

2.5.4 RLV-Intensive Controlled Airspace

Keeping the current SUA intact but allowing controlled aircraft to enter may alleviate some of the disruption introduced in air traffic flow while the SUA is active. Thus, actively controlled aircraft might be allowed into the SUA provided that there is clearance from the ROC. One concept would be to relabel space-operation SUA as “Class H” airspace, with similar requirements to current Class B airspace, except that any aircraft may be denied entry by ATC if a space operation is occurring.

During RLV operations, ATC is notified of what airspace, including safety buffers inside the

SUA, will be needed for RLV operations. The expected RLV operation time will also be communicated. ATC maintains communications with the ROC for updates or changes in the operations. Then, as required, ATC vectors air traffic in Class H airspace around RLV routes. Permission for VFR aircraft to enter the Class H airspace may be granted on a workload-permitting basis.

> **Pros:** The spatial and temporal impact on air traffic is reduced, and pilots are freed from needing detailed knowledge of airspace requirements and RLV operations.
>
> **Cons:** Close communication and coordination is required between ATC and ROC. All aircraft need to be under positive control, increasing controller workload, and transponder and other equipment requirements.

2.5.5 Controlled Airspace with Real-Time RLV Corridor

The ROC or the RLV itself communicates a flight plan and airspace corridor requirements to ATC in real time. ATC then dynamically performs corridor updates in response to RLV state, and vectors traffic around the corridor. Otherwise the operation is similar to Class H case.

> **Pros:** The impact (primarily temporal) on air traffic is reduced compared to Class H, but the gain may be inconsequential.
>
> **Cons:** New prediction methods, displays, and procedures are required. The safety buffer is reduced. All aircraft are required to be under positive control and controller workload is increased

2.5.6 RLV as a High-Priority Vehicle

Treats the RLV similar to aircraft, with equivalent requirements (files a flight plan, obtains a departure clearance, etc.). However, for separation assurance, the RLV is given priority or right-of-way over other air traffic. ATC has responsibility for separation and needs improved guidelines on detecting conflicts to respond appropriately to RLV requirements. RLVs behave differently from conventional aircraft with high velocities and vertical rates and limited maneuverability. The appropriate form of the flight plan also needs to be determined.

Prioritization issues may be more critical with RLVs. If aircraft are given lower priority than RLVs, flight delays and airlines’ costs increase. RLVs often have tight launch windows and any delay due to a prioritized aircraft might cause the operation to be cancelled. Vectoring the RLV around conflicts is possible if the RLV is maneuverable and if resolution doesn’t impact the mission plan. It may be necessary to change prioritization as a function of phase of flight. How prioritization is conveyed to ATC and the aircraft needs to be determined.

> **Pros:** The impact on air traffic is reduced and the operation is more seamless
>
> **Cons:** RLV and/or ROC communications are required with ATC to provide flight plan, tracking, and prediction information. Safety buffer is reduced and controller workload increases.

2.5.7 RLV as a Nominal-Priority Vehicle

The RLV is treated the same way as other air traffic. ATC has responsibility for separation. ATC needs improved guidelines and prediction methods for detecting conflicts to account for the flight characteristics of the RLV such as high velocity and vertical rate, and limited maneuverability.

> **Pros:** The impact on air traffic is reduced and the operation is more seamless.
>
> **Cons:** Negative impact on RLV operation results as it may be asked to avoid aircraft. RLV/ROC communications are required with ATC (flight plan, tracking, prediction). The safety buffer is smaller. ATC and controller workload increases.

2.5.8 RLV - Aircraft Self-Separation

Aircraft and RLVs self-separate using on-board systems and procedures. Many issues remain to be resolved even with “conventional” aircraft vs. aircraft self-separation. These issues are exacerbated in cases involving high-performance RLVs. The RLV typically enters and exits airspace in a short time span (~5 minutes), and the time available for decision making is more limited. Vertical profiles, which are difficult to display, are critical to RLV separation. Predictive information, if available, would also be useful.

> **Pros:** The impact on air traffic is reduced and the operation is more seamless. ATC and controller workload possibly decreases.
>
> **Cons:** Negative impact on RLV operation results as it may be asked to avoid aircraft. RLV/ROC communications are required with aircraft and ATC. The safety buffer is smaller. Pilot workload and responsibility increases

2.6 Air Traffic Control Issues

2.6.1 Separation Factors

Several factors influence the requirements on safety buffer size when operating in the vicinity of an RLV. Traditionally, the direct collision between vehicles has always been a major concern. Sensor capabilities, guidance accuracy, encounter geometry, and maneuverability all affect the need for a given separation standard. Additionally, vehicle wake vortex concerns dictate in-trail separation requirements.

With RLVs, several additional issues must be considered:

- Exhaust / chemical plume / smoke
- Expended stages
- Auxiliary operations: chase planes, weather soundings
- Potential for catastrophic failure
    - departure from planned trajectory
    - explosion / debris

Taken together, the additional uncertainties in these last factors (especially the potential for catastrophic failure) result in the need for a large safety buffer.

2.6.2 Current Aircraft Separation Standards

The current air traffic system is built around stratified flight levels. Aircraft generally cruise at constant altitude and the controller has a planform (2D) view of traffic. Typical vertical rates range between 1,000 - 2,000 ft/min with 4,000 ft/min as an extreme case. Radar update rates are 12 seconds enroute and 4 seconds in the terminal areas.

RLVs may have significantly larger vertical rates. The space shuttle (STS) has a 12,000 ft/min nominal descent rate, which is 4 to 6 times larger than conventional aircraft, and descends from 80,000 ft to touchdown in approximately 6 minutes. Predicting conflicts under such conditions becomes much more difficult without additional information.

Current aircraft separation standards are 5 nmi horizontally, and 1000 ft vertically (2000 ft above 29,000 ft). The bases for these limits are procedural and are principally based upon experience rather than derived analytically. Vertical separation standards are generally based on altimetry accuracy, while horizontal separation requirements are based in part on radar position accuracy, operational experience, and controller / pilot response time.

Current vertical and horizontal separation standards are under re-evaluation. Only limited established criteria exist to determine ‘safe’ aircraft-RLV separation. However conventional separation standards can still be used as baselines for comparison with other options.

2.6.3 TCAS and RLVs

Systems such as the Traffic Alert and Collision Avoidance System (TCAS) will need enhanced logic and sensor capabilities to manage RLV-type threats. Current TCAS logic does not track closure rates greater than 1200 kt, and relative vertical rates greater than 10,000 ft/min. Based on these limitations, acceptable TCAS operation with RLVs is questionable with the current design. However, the potential for time-critical separation using TCAS was briefly examined as described below.

Assume that TCAS can track an RLV descending at a 12,000 ft/min descent rate. An encounter scenario was postulated with a head-on conflict between an aircraft flying level and an RLV descending at 12,000 ft/min, with both vehicles at 500 kt. Simulating the encounter with ideal TCAS logic (i.e., no state filter model), a collision is projected unless an avoidance maneuver is performed. Figure 2-7 shows a vertical profile of the encounter following a TCAS Resolution Advisory for both an RLV and a conventional aircraft.

The TCAS vertical alert thresholds for this case are:
TA: 48 sec = 9,600 ft relative altitude
RA: 30 sec = 6,000 ft relative altitude
(where TA is the Traffic Advisory, and RA is the Resolution Advisory).

If the aircraft performs a standard TCAS avoidance maneuver (5 second response delay after RA, 0.25 g pull-up to 2000 ft/min), the vertical separation at the closest point of approach is 769 ft. The vertical miss-distance is the same regardless of descent rate for this example. However, the horizontal range at co-altitude crossing is only 5,000 ft for the RLV, as opposed to 19,000 ft with a conventional-aircraft case at 2,000 ft/min (Figure 2-7). The TCAS avoidance maneuver has a reduced effect as the descent rate increases, because the resolution is only performed in the vertical direction.

2.7 Conclusions

The preliminary recommendation based on the results of Phase I are, that because of its operational simplicity, SUA should generally be used unless a significant negative impact on air traffic is identified. SUA is relatively simple to activate, and procedures can be developed by ATC to reroute traffic. SUA also provides a large degree of safety and the most flexibility for the space operation when compared to other concepts.

However, certain RLVs operate similarly to aircraft during certain phases of flight, and therefore may be good candidates for a more mixed mode of airspace allocation. An example would be an RLV such as Pegasus, in which there may be a significant cruise/ferry phase of flight during which speed and vertical rate are similar to other air traffic. During this phase of flight, air traffic and the Pegasus carrier could be managed using conventional ATC procedures. The Pegasus carrier might then transition to SUA where the launch of the rocket-powered stage of Pegasus could be performed safely.

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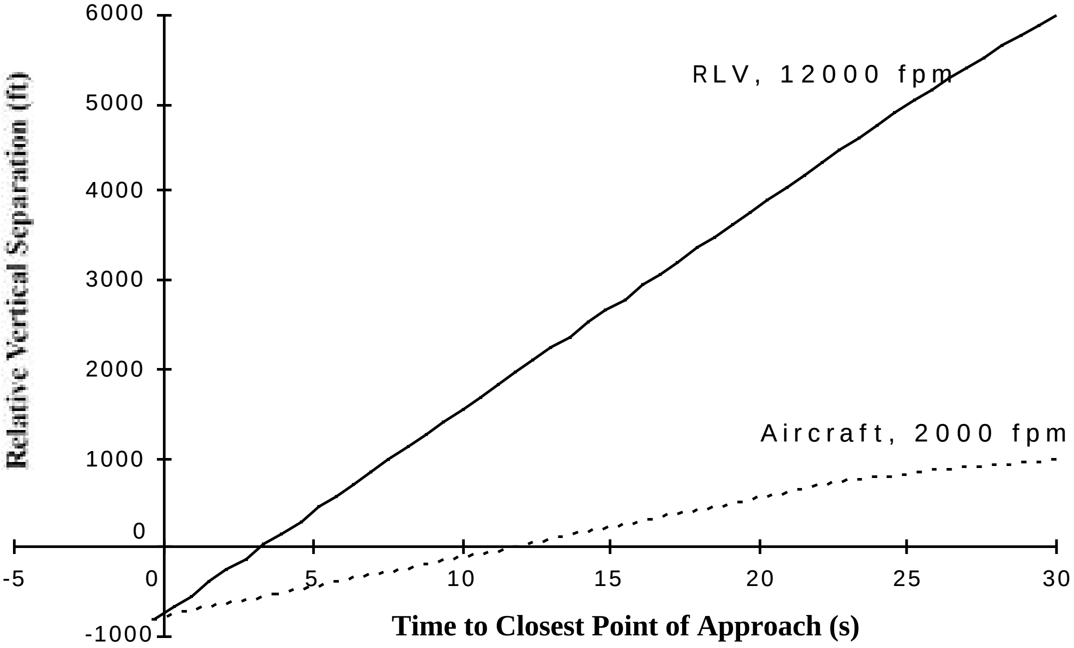

Figure 2-7: Example TCAS RLV Encounter

More complex concepts, such as allowing controlled aircraft into SUA, may provide traffic flow benefits, but will likely require significant improvements to technologies on aircraft and at ground control stations. Additional controller tools, communications, and procedures will also be needed.

To address these issues, additional research is required to determine the actual technological requirements and constraints on integrating RLVs with air traffic. Of primary concern is the ability of the current or proposed ATM systems to accurately track and predict the trajectories of RLVs.

A second area of research is needed regarding the roles of the human operators and controllers. For example, SUA has the advantage of being relatively simple to activate, with well-defined procedures and boundaries, and ATC can vector traffic around the area without undue workload. A more tactical RLV airway, however, may require the activation of a different region of airspace with each launch, necessitating a means of efficiently providing traffic controllers with the necessary information and aids to vector traffic.

2.7.1 Phase II Plan

These issues are being addressed as part of Phase II of this project. Phase II is organized into several research topics, outlined below.

1. Tracking and Estimation. Uncertainties in RLV position and trajectory translate into uncertainty in when, where, and how to clear traffic from the projected flight path. A balance is required between an overly-conservative system that unnecessarily reroutes traffic and a system that warns traffic of a conflict only when relatively aggressive maneuvering is required. Studies will be performed to determine requirements on tracking accuracy and update rate for the candidate modes of operation. A probabilistic framework that has been used to evaluate traffic and terrain alerting systems will be applied to the RLV conflict situation. This approach allows key tradeoffs to be determined, for example showing the relationship between sensor accuracy and a required airspace safety buffer size. With the addition of cost and implementation issues and the impact on air traffic flow (from parallel work ongoing at VT), recommendations can then be made regarding appropriate sensor requirements.

2. Humans and Automation. Certain methods of operating may appear reasonable based on technical requirements such as sensors, but may be infeasible due to liens placed on human operators. Because RLVs may travel at speeds much larger than aircraft, the use of conventional procedures and displays of traffic information may be inadequate. A part-task simulation study will be developed to investigate the ability of pilots and controllers to manage RLV-aircraft conflicts using current and prototype advanced displays and procedures. Studies may include flight deck notification of Special Use Airspace activation via radio vs. graphical display using datalink, or evaluation of prototype displays for conflict alerting and resolution.

3. Provide Operating Recommendations. Based on the evaluations, recommendations will be provided for the candidate modes of operation that have been examined. These recommendations may include single design points (e.g., sensor accuracy must be greater than x) and may include a description of the design tradeoff to allow future efforts to determine the appropriate operating point (e.g., to quantify the benefits as sensor accuracy is increased).

4. Identify Future Areas of Study. Once the principal issues have been defined and explored, recommendations for follow-on studies will be made. This may include large-scale simulation of RLV and air traffic, high fidelity cockpit simulations, etc.

3.0 Summary of the Virginia Tech Effort

3.1 Analysis of Traffic Operations Around Launch Sites

Traditional means of separating launch vehicles from subsonic transport and general aviation operations has been carried out using Special Use Airspace (SUA). This approach is quite conservative because it prohibits commercial and general aircraft operations over large portions of NAS or over the ocean for periods of time prior to launches and during expected reentry procedures. The expected growth in the number of commercial launches in the next few years drives the FAA need to quantify the impacts of RLV operations in the aircraft traffic flows around spaceports. The following paragraphs detail some of the modeling efforts pursued at VPI in support of the RLV integration into the ATC system of the future.

3.1.1 Phase I Objectives

The objectives of the VPI segment of Phase I were to:

- Investigate methods to evaluate the cost of RLV operations under various operating modes
- Develop a framework to be used in this economic evaluation
- Provide recommendations for further study and implementation
- Assess the economic cost/benefit analysis

3.2 RLV Impact Assessment Methodology

Over the past year VPI has developed an impact assessment methodology to estimate the economic impacts of RLV operations today and in the future NAS. The framework developed attempts to quantify the costs of various models of RLV operations as they would affect commercial and general aviation aircraft in NAS. The framework goes beyond the simple estimation of costs associated with flight operations and involves the development of an optimization procedure to minimize flight disruptions considering costs to service providers (FAA), users, and non-users.

In Phase I, the VPI research team has identified models and methods to quantify costs of RLV operations in NAS. The approach devised consists of two modeling strategies:

1) A cost model to determine the economic impact of using SUA (i.e., implementing flight trajectory diversions) and,
2) An optimization model to minimize the impact of RLV operations through a reconfiguration of flight schedules.

Progress has been made in the development of these two models and they have been tested with simple airspace scenarios to verify the approach taken (see Figure 3-1).A sample model implementation is shown in Section 3.5.11 of this report.

The model developed is primarily intended to quantify costs associated with ATC system interventions in a waypoint-based or a Free Flight structure (see Figure 3-2). This model also serves as input to an optimization program developed to minimize ATC interventions, costs to users, or a combination of these two indices. In this case the model generates Gantt charts corresponding to enroute sector conflicts expected to occur in a constrained NAS environment. The constraints modeled inhibit unresolved conflicts, account for workload restrictions over the involved ATC sectors, and attempt to achieve an equity among users (airline companies) with respect to incurred delays. The objective function reflects various user-related operational costs as well as conflict resolution penalties. The resulting optimization model possesses special structures that can be exploited in designing suitable mathematical programming solution techniques.

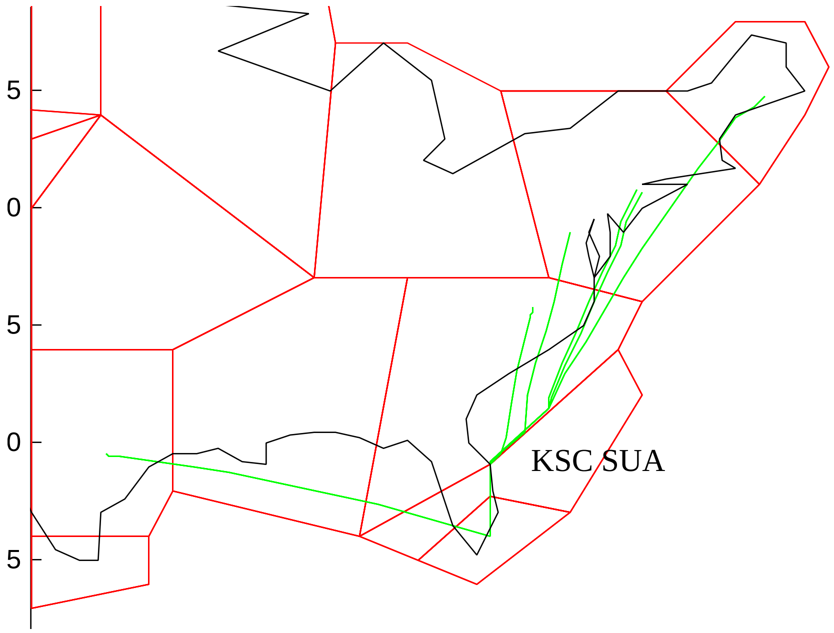

Figure 3-1: Graphical Flight Path Simulation/Optimization Model Pre-processor

In parallel to the models under development, proven airspace simulation models (i.e., SIMMOD and RAMS) will also be used in Phase II to identify costs associated with existing fixed-route and Free Flight airspace flight profiles. Both of these models are available to the COE research team.

Figure 3-2 illustrates the proposed approach in Phase II to quantify the economic impact of RLV operations in NAS. This approach uses an optimization model (currently under development) and existing simulation models to quantify cost/benefits in Free Flight mode or constrained (fixed) route airway systems.

The detailed RLV operational modes examined by MIT (upper left box in this figure) will be translated into a sector restriction database file structure (see Figure 3-2). This database is then fed to airspace simulation and optimization models (SIMMOD and RAMS) to generate costs of alternative RLV operational modes. This process requires a large ATC database describing existing sectors (i.e., treated as convex sets) and a working set of flight plans estimated from ETMS data, extracted from the official airline guide, or generated from a Free Flight trajectory subprogram developed at Virginia Tech. Cost metrics (i.e., fuel consumption, travel times, workload patterns) are derived from outputs of the simulation model and from the pre-processor functions required to feed the data into the optimization model (right hand side box in Figure 3-2). The optimization model constitutes a research function that perhaps FAA traffic managers would want to consider to reduce user costs or minimize conflicts in a dynamic ATC environment (i.e., reduce controller workload). At the same time this is one meaningful way to assess ATC workload constraints that could eventually be translated into FAA costs.

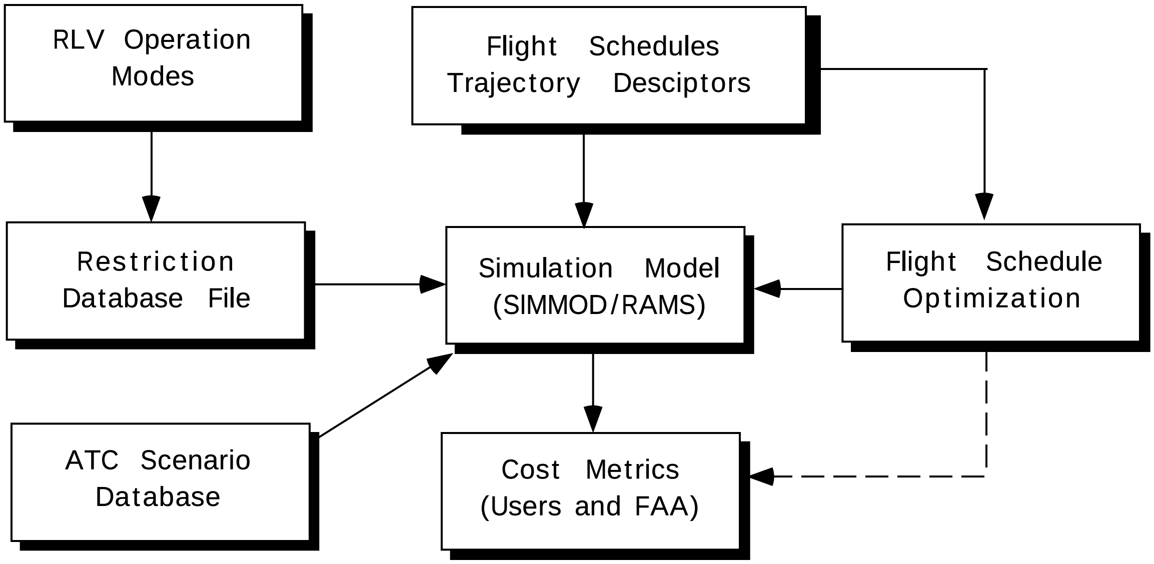

Figure 3-2: RLV Impact Assessment Methodology

3.3 Modeling and Simulation of Aircraft Operations

The modeling and simulation function described here is necessary to have confidence in the results obtained in the optimization model. Moreover, it is important to gain some insight on how much advanced Air Traffic Management procedures can mitigate RLV impacts at spaceports. SIMMOD - the FAA airspace and airfield simulation model and RAMS - Eurocontrol reconfigurable airspace simulation tool are used in this context to track travel times, predict delays, conflicts, airport congestion, etc. All these are necessary inputs to assess the cost of RLV operations. Figure 3-3 illustrates a sample airspace scenario using RAMS.

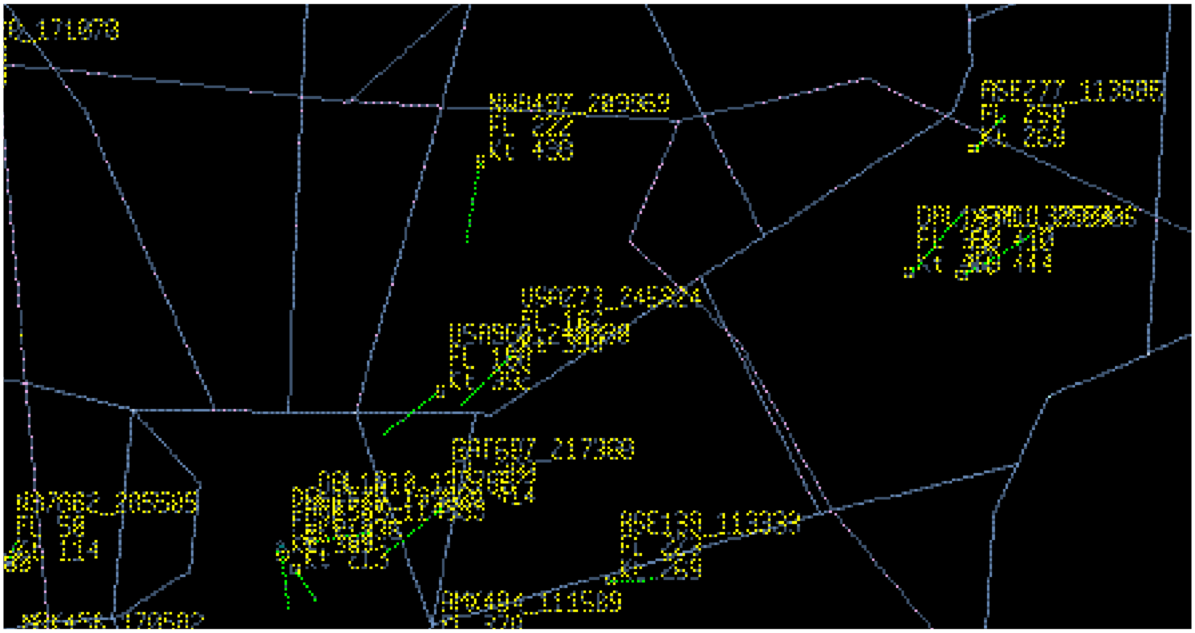

Figure 3-3: Sample Airspace Scenario Using RAMS.

3.4 Optimization Model to Mitigate RLV Impacts

In order to minimize the impacts of RLV operations at various spaceports an optimization model has been developed to consider commercial and general aviation economic impacts, ATC system constraints (i.e., workload) and operator equity constraints. The following paragraphs constitute a description of such model.

Consider a planning horizon H, and suppose that we are given a set of flights $i = \{1, \ldots, m\}$ covering this horizon that are relevant to interactions with a particular RLV spaceport. Let $M = \{1 \ldots m\}$. Note that there might be other extraneous flights that are unaffected by this spaceport operation, but that interact between certain fixes with flights that are affected by such operations. We will assume that flight plans are known for such extraneous flights and are not part of the present decision process. (However, such flights do pay a role in ascertaining workload and conflicts below.)

For each flight, $i \in M$, let

P_i = {set of possible flight plans p composed of departure times and flight levels between designated fixes along the route from the corresponding origin to the corresponding destination}.

Note that there will typically exist some preferred departure time for each flight, along with some alternative (discrete) departure schedules. For each departure time, a flight plan can be generated using some commercial package, such as JEPPESSEN FliteStar or Data Plan, for example. This plan would be naturally dependent on the spaceport operations during the journey of the flight. Possibly, more than one flight plan could be considered as an alternative for a given departure time. (We can also develop a new flight plan generator based on a time-space network representation of the airspace.)

Now, given any combination (i, p), $i \quad M$, $p \quad P_i$, we can compute a cost factor c_{ip} for adopting plan p for flight i. (SIMMOD - the FAA airspace and airfield simulation model and RAMS - the Eurocontrol reconfigurable airspace simulator are used for this purpose.) This cost would reflect fuel expended, delay costs, as well as penalties or benefits (rewards or negative penalties) based on safety considerations and the selection of a corresponding departure time.

Accordingly, defining the *decision variables*

$$x_{ip} = \begin{cases} 1 \text{ if plan } p \quad P_i \text{ is adopted for flight } i \quad M \\ 0 \text{ otherwise} \end{cases} \qquad i \quad M, p \quad P_i \qquad (1)$$

we can formulate a total system-based objective function to

$$\text{Minimize} \sum_{i \quad M} \sum_{p \quad P_i} c_{ip} x_{ip} \qquad (2)$$

The constraints would include the selection of a plan for each flight as specified by

$$\sum_{p \quad P_i} x_{ip} = 1 \qquad i \quad M, \qquad (3)$$

as well as certain equity, workload and conflict resolution restrictions as discussed next.

Equity Constraints:

Suppose that there are some F airline firms involved in this study, indexed by $f = 1, \quad , F$. In the process of selecting flight plans based on (2) and (3) (in addition to workload and conflict resolution constraints as described in the sequel), we would also like to achieve a degree of equity among the airline firms. For each firm f = 1,...,F, let us define a measure of *ineffectiveness* M_f as

$$M_f = \sum_{(i, p) \quad A_f} \alpha_{ip} x_{ip} \qquad (4a)$$

where

$$A_f \quad A_f \equiv \{(i, p) \text{ flight belongs to firm f}\}, f = 1, \quad , F. \qquad (4b)$$

Defining the variables x_l^e and x_u^e to represent the (variable) range for the ineffectiveness measures M_f, f = 1,...F, where the upper limit x_u^e of this range is restricted to be no more than some specified value n_e, we can model equity via the following generalized constraint.

Include within constraints:

$$x_l^e \le \sum_{(i,\,p)\varepsilon A_f} \alpha_{ip} x_{ip} \le x_u^e \qquad f \;=\; 1, \quad , F \tag{5}$$

$$x_l^e \ge 0,\, x_u^e \le n_e \tag{6}$$

Include within the objective function:

$$\text{(Minimize)} \qquad + \mu_e(x_u^e - x_l^e) + \mu_u^e x_u^e \tag{7}$$

where μ_e is a (commensurate) penalty per unit of variation in the measures M_f, $f \;=\; 1, \quad , F$,and μ_u^e is a (commensurate) penalty for the maximum incurred measure of ineffectiveness. Note that if restricting $x_u^e \le n_e$ is sufficient, we could take $\mu_u^e \equiv 0$. On the other hand, in order not to overly restrict the problem, n_e could be taken as the maximum tolerable limit on any M_f value, and then the penalty μ_u^e would serve to reduce x_n^e below n_e to the extent possible or desirable.

Remark 1. The variables x_l^e and x_u^e can be fixed at their respective bounds of 0 and n_e if so desired. In this case, each measure M_f is simply restricted to be no greater than n_e, for f = 1,...,F, and the constraints $M_f \ge x_l^e \equiv 0$ in (5) may be omitted.

Special Cases. The following are some special cases of the equity modeling constraints (5)-(7). In each case, x_l^e and x_u^e can be treated as variables as in (5) and (6), or be fixed as mentioned above in Remark 1.

Case(i): $A_f = U_f$, where

U_f = {(i,p) : flight plan (i,p) belongs to firm f and is undesirable} $\quad f \;=\; 1, \quad , F,$ (8)
and $\alpha_{ip} \equiv 1 \quad (i,\, p)$. This restricts the number of undesirable flight plans selected for each firm to be no more than n_e, and strikes a balance between the firms.

Case(ii): $A_f = A_f \quad f = 1, \quad , F$, and α_{ip} = delay (d_{ip}, say) for flight plan (i,p). This case seeks an equity with respect to total delay. Note that in lieu of delay, any other “cost” measure could be used in this context.

Case(iii): Since the number of flights n_f, say, that belong to the various firms f = 1,...,F might differ quite widely, it is more appropriate to seek equity with respect to the average delay (or cost), as opposed to the total delay considered in Case (ii) above. Accordingly, we can use $A_f = A_f \quad f = 1, \quad , F$, and

$$\alpha_{ip} = \frac{d_{ip}}{n_f} \text{ for each } (i, p) \quad A_f, f = 1, \quad , F. \tag{9}$$

Case(iv): Similar to the normalization of Case (ii) via Case (iii), we can normalize Case (i) by considering equity among the fraction of flights selected for each firm that are undesirable. Accordingly, we can set

$$A_f = U_f \quad f = 1, \quad , F, \text{ and } \alpha_{ip} = \frac{1}{n_f} \text{ for each } (i, p) \quad U_f, \ f = 1, \quad , F \tag{10}$$

Case(v): All the foregoing discussion pertains to "minisum" measures of ineffectiveness. Alternatively, we can consider a "minimax" strategy that attempts to minimize the maximum delay (or cost) d_{ip}, incurred by any selected flight plan. Hence, we would fix $\mu_e = 0$ and and $x_i^e = 0$ in this case, and replace (5) and (6) by

$$x_u^e \ge d_{ip} x_{ip} \qquad (i, p) \quad A_f, f = 1, \quad , F \tag{11}$$

Note that in this case, the *overall* objective function is reduced to a combination of a minisum and minimax objective. Of these alternatives, we recommend the use of Case (iii) or Case (iv), embodied by Equations (9) or (10), respectively, along with Equations (5)-(7).

Workload Constraints:

Consider the total collection of flight plans $\underset{i \quad M}{} P_i$. Jointly, these plans involve traversals between certain pairs of fixes, as well as free-flight cruises between designated pairs of fixes, at various specified flight levels. Let us consider a segmentation of the airspace into sectors as defined by FAA (i.e., polygons, lifted into the third dimension). Define the *workload* for a sector at any point in time to be the number of aircraft in that sector at the given instant of time. Let

$$S = \{\text{set of all sectors involved with the collection of flight plans } \underset{i \quad M}{} P_i \}. \qquad (12)$$

For each sector $s \quad S$, we can now examine the occupancy durations of the flights $i \quad M$ over the horizon H, in concert with the occupancy durations of any extraneous flights as described above. Note that whenever we have an overlap of such occupancy durations, we have an increase in workload. In practice, Air Traffic controllers routinely handle several aircraft in their sectors successfully. Of course, when the workload becomes too high, a potentially dangerous or untenable situation can arise. Hence, let us define the following entities.

For each $s \quad S$, let $k = 1, \quad, K_s$, be a total collection of maximal overlapping sets of flight plans (i, p), where an overlapping set of flight-plans is called *maximal* if it is not a strict subset of another overlapping set. For example, examining Figure 3-4, we have four such maximal sets given by $\{ (i_1, p_1), (i_2, p_2), (i_3, p_3) \}$, $\{ (i_2, p_2), (i_3, p_3), (i_4, p_4) \}$, $\{ (i_3, p_3), (i_4, p_4), (i_6, p_6) \}$, and $\{ (i_5, p_5), (i_6, p_6) \}$. Let us denote these sets by C_{sk} for $k = 1, \quad, K_s$, (where K_4, = 4 in the example of Figure 3-4). Hence,

$$C_{sk} = \{ (i, p) : \text{flight plan } (i, p) \text{ belongs to the } k^{th} \text{ maximal overlapping set for sector } s \}, \quad k = 1, s \quad S \qquad (13)$$

Note that it is possible that if (i_1, p_1) and $(i_2, p_2) \quad C_{sk}$, then $i_1 = i_2$, i.e., this pair corresponds to the same flight, although in this case, the flight plans would be distinct. We would now like to impose that there be no more than some n_{sk} resident simultaneous aircraft in a sector from among the ones that appear in C_{sk}, i.e.,

$$\sum_{(i, p) \quad C_{sk}} x_{ip} \le n_{sk} \qquad k = 1, \quad, K_s \text{ and } s \quad S \qquad (14)$$

The parameters n_{sk} can be chosen by the user to be dependent on the particular sector and the nature (type and number) of the overlapping flights. Also, note that by virtue of (3), a given flight would at most contribute a unit to the left-hand side of (14).

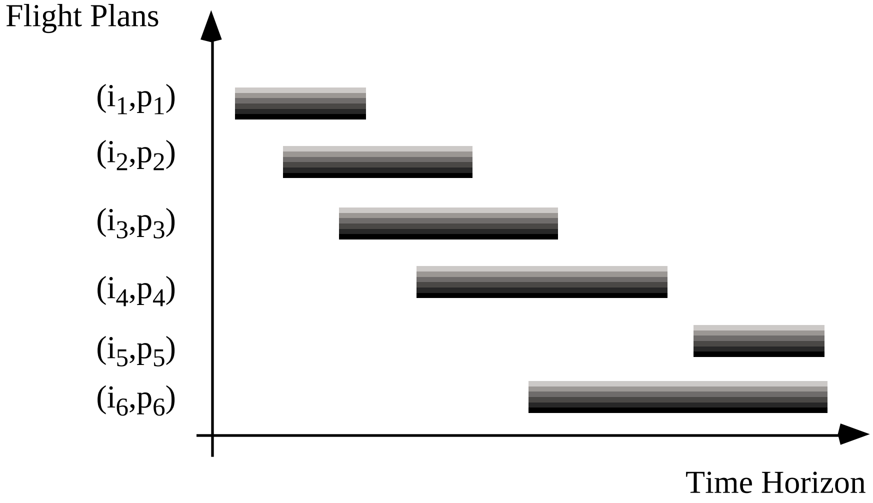

Figure 3-4: Sample Flight Plans over Time Horizon

Remark 2. The reason for selecting maximal sets is to obtain a minimal nonredundant set of constraints in (14). For any overlapping set that is not *explicitly* represented in (14), this set must be a subset of some set that appears in (14). If the restriction on the permissible number of aircraft for this former set is at least as large as that for the latter (for some such case), then a constraint of type (14) based on this former set is redundant. Otherwise, we would need to explicitly include such a constraint within (14). Henceforth, we will assume that (14) includes all possible nonredundant workload constraints of this type.

A preliminary model based on the development thus far is stated below.

$$\text{Minimize} \sum_{i \quad M} \sum_{p \quad P_i} c_{ip} x_{ip} + \mu_e (x_u^e - x_l^e) + \mu_u{}^e x_u^e \qquad (15a)$$

$$\text{subject to} \sum_{) \quad P_i} x_{ip} = 1 \qquad i \quad M \qquad (15b)$$

$$\sum_{(i,p) \quad C_{sk}} x_{ip} \le n_{sk} \qquad k = 1, \quad , K_s \text{ and } s \quad S \qquad (15c)$$

$$x_l{}^e \le \sum_{(i,p) \quad A_f} \alpha_{ip} x_{ip} \le x_u^e \qquad f = 1, \quad , F \qquad (15d)$$

$$x \text{ binary}, \; x_l^e \ge 0, x_u^e \le n_e \qquad (15e)$$

Note that (15a) is a 0-1 programming problem that possesses special partitioning and generalized packing constraints described by (15b) and (15c), respectively. This structure can be exploited in devising special algorithmic schemes. (Alternatively, automatic reformulation techniques, such as RLT, can be used to enhance the model itself before solving it via a commercial package such as CPLEX-MIP.)

Remark 3. In the foregoing model, we could let the maximum number of overlapping flights permitted within each segment $s \quad S$ be a *variable* n_s bounded by the interval $[0, \overline{n}_s]$, say, and we could accordingly penalize its value in the objective function. If a linear penalty term is used, this would simply involve replacing the right-hand side in (15c) by n_s, where $0 \le n_s \le \overline{n}_s \quad s \quad S$, and incorporating an appropriate linear cost term in the objective function. However, it might be more suitable to impose a nonlinearly increasing penalty factor with an increase in workload. That is, if the maximum number of aircraft in a sector increases from one to three, the associated penalty should likely be more than triple. Hence, let us define the binary variables

$$y_{sn} = \begin{cases} 1 \text{ if the maximum workload in sector } s \text{ is } n \\ 0 \text{ otherwise} \end{cases} \quad s \quad S, n = 1, \quad , \overline{n}_s$$

and let μ_{sn} be the associated penalty for having $y_{sn} = 1$. Then, Model (15) would be modified as follows.

$$\text{Minimize} \sum_{i \quad M} \sum_{p \quad P_i} c_{ip} x_{ip} + \sum_{s \quad S} \sum_{n=1}^{\overline{n}_s} \mu_{sn} y_{sn} + \mu_e (x_u^e - x_l^e) + \mu_u{}^e x_u{}^e \qquad (15'a)$$

$$\text{subject to} \sum_{p \quad P_i} x_{ip} = 1 \quad i \quad M \qquad (15'b)$$

$$\sum_{(i,p) \quad C_{sk}} x_{ip} - n_{sk} \le 0 \quad k = 1, \quad , K_s, s \quad S \qquad (15'c)$$

$$x_l^e \le \sum_{(ip) \quad A_f} \alpha_{ip} x_{ip} \le x_u^e \quad f = 1, \quad , F \qquad (15'd)$$

$$n_s = \sum_{n=1}^{\overline{n}_s} n y_{sn} \quad s \quad S \qquad (15'e)$$

$$\sum_{n=1}^{\overline{n}_s} y_{sn} \le 1 \quad s \quad S \qquad (15'f)$$

$$(x, y) \text{ binary}, \ x_l^e \ge 0, x_u^e \le n_e \qquad (15'g)$$

Note that n_s can be treated as a continuous variable in (15’), and its bounding and integrality restrictions are implied by (15’ e-g).

Remark 4. Observe that for each flight plan combination, (i, p), we can examine the number of times x_{ip} appears in the constraint set (15c) in order to assess the degree of the workload being generated by this flight plan. This indicator can be used to prompt the generation of alternative plans for a given flight, based on the degrees of workload associated with its current set P_i.

Conflict Constraints

Let us discretize the horizon into suitable time slots that are such that while not being too small (in order to contain the computational effort and model size), they are sufficiently small so that the following hold true:

(A1) If we view the position of each aircraft, at each of these discretized points in time (say midpoints of each interval), then if there is no conflict recognized over consecutive discrete time periods, there would be no conflict if the situation were viewed contiguously.

(A2) The size of the time intervals are such that it is meaningful to impose the restriction that for each sector, the maximum number of (permissible) conflicts that need to be resolved for each time period should not exceed 1.

Next we perform a discrete event simulation advancement of all the aircraft-plans in the problem, one period at a time. For each time period, we establish the positions of the different aircraft plans and record the following:

(a) The occupancy of the different sectors by the aircraft (this would be coordinated with the delineation of the foregoing workload constraints).

(b) Suppose that aircraft i has an *interference domain* of radius r_i that defines its surrounding airspace, and a *circumscribing sphere* surrounding the aircraft of radius c_i. A pair of flight plans (i,p) and (j,q) (henceforth denoted as “P” and “Q” respectively), where $i \neq j$, would be in conflict if the distance D(P,Q) between aircraft i and j is lesser than $\max\{(r_i + c_j), (r_j + c_i)\}$. If the conflict is untenable (by some defined measure that we can stipulate), we would immediately impose a constraint that permits the selection of at most one such flight plan. Denoting FC as the set of such “fatally conflicting” pairs of flight plans, we begin by stipulating that

$$x_P + x_Q \leq 1 \text{ for all } (P, Q) \quad FC. \qquad (16)$$

Remark 5. Note that a particular flight plan that traverses through some sector *s* might be in conflict by the foregoing definition with another flight plan that occupies a different sector *s*’. Since this situation adds to the potential workload of both sectors *s* and *s*’, we include within the Gantt chart for each of these sectors the flight plan that belongs to the other sector for the duration over which this conflict persists. Hence the workload constraints of the previous subsection accommodate such extraneous occupancy intervals as well. Observe that another alternative might be to extend the boundaries of each sector by an appropriate amount so that the sectors provide an overlapping coverage of the enroute airspace, and then to formulate the workload constraints in the usual fashion as described before. However, for now, we will adopt the former strategy because of the standard data files used by the FAA to record sector designations.

To formulate the conflict constraints, suppose that we construct a graph $G_t(N_t, A_t)$ for each given time period t, where N_t is the set of nodes (i,p) for all flight plans, and A_t is the set of edges such that if P and Q are in conflict during this period t, then A_t includes an edge joining these corresponding nodes. Since we have explicitly excluded non-permissible conflicts via (16) above, we can restrict our attention to recording via A_t just the *permissible conflicts*, that is, conflicts that can be measured by some defined measure. This graph would typically be a collection of (disjoint) components. For each sector *s*, let $G_{st}(N_t, A_t)$ be a subgraph of G_t that is composed of those components of G_t for which at least one of the nodes in this component is in sector *s* at time *t*. (Alternatively, G_{st} can be defined as follows. Let N_{st} contain all the nodes that belong to sector *s* at time t, along with any adjacent nodes from the graph G_t. Then define A_{st} as a set of arcs from A_t that have both the end points included in N_{st}, i.e., G_{st} is the subgraph induced by N_{st}. The defined construction of G_{st} would need to compromise between effort versus representation, but the general concept behind G_{st} is to obtain a graph that represents conflicts between pairs of flight-plans that sector *s* needs to participate in resolving during time period t.). We now impose the constraint that:

"*No more than one permissible conflict should occur for each sector during each time period*".

To model this constraint, for each sector, consider the edges in A_{st} taken two at a time, and each pair *k*, let S_k be the set of nodes at which this pair of arcs is incident. $|S_k|$ equals three or four, depending on whether the pair of edges is adjacent or not. The imposed constraint would then be

$$\sum_{P \quad S_k} x_P \le |S_k| - 1 \tag{17}$$

Note that there would be $|A_{st}|(|A_{st}| - 1)/2$ equations of the type (17) for each sector, for each time period. (We assume that the index k runs contiguously over these constraints for all s, t.) Observe that there will likely be several redundant constraints established via this process. In particular, the following result holds true.

Proposition 1. Consider a pair of constraints of the type (17) for some sets S_1 and S_2 say, such that $S_1 \quad S_2$. Then (17) for S_2 is redundant (even in the continuous sense) and can therefore be deleted.

Proof. Let us show that (17) for S_1 implies for S_2. Given that (17) holds for S_1, we have that

$$\sum_{P \in S_2} x_P = \sum_{P \in S_1} x_P + \sum_{P \in S_2 - S_1} x_P \le |S_1| - 1 + |S_2 - S_1| = |S_2| - 1 .$$

This completes the proof.

For example, if we had a conflict graph comprised of nodes 1,2,3, and 4 with edges (1,2), (2,3), (1,3), and (3,4), then the pair of edges (1,2) and (1,3) impose the constraint that

$$x_1 + x_2 + x_3 \le 2$$

while the edges (1,2) and (3,4) impose that

$$x_1 + x_2 + x_3 + x_4 \le 3$$

which is implied by the former. Procedure 1 below presents a scheme for directly generating only nonredundant elements of (17).

Overview of Procedure 1 First, constraints (17) are generated for al adjacent pairs of edges. These constraints may be duplicates if the set of nodes involved form a clique. The procedure recognizes this structure to avoid generating a copy of a pre-existing constraint. For all remaining pairs of edges, a constraint is generated only if it is not already implied by the constraints generated from the adjacent pairs of edges.

Details for Procedure 1. Define a node adjacency matrix E having elements E(P,Q) =1 if nodes P and Q have a connecting edge for each P<Q, and 0 otherwise. We will let E(P-Q) denote E(P,Q) if P<Q, E(Q,P) otherwise.

Step 1: Generate (17) for adjacent edges.

```
for each row P,
    for each entry E(P,Q)=1, Q>P
        Generate (17) corresponding to edges (P,Q) and (P,K) where E(P,K)=1 and Q<K
        Generate (17) corresponding to edges (P,Q) and (H,Q) where E(H,Q)=1,P<H<Q,
        and $E(P, H)) \ne 1$.
    end
end
```

Step 2: Generate (17) for non-adjacent edges.

```
for each row P,
    for each entry E(P,Q)=1, Q>P
        for each row M>P, $M \neq Q$
            for each column N>M such that E(M,N)=1, $N \neq Q$, $E(P, N)) \neq 1$
                if $E(Q - M) \neq 1$ and $E(Q - N) \neq 1$
                    Generate (17) corresponding to edges (P,Q) and (M,N)
                end
            end
        end
    end
end
```

Remark 6. Note that depending on the duration of each time slot relative to the horizon, the discrete event simulation process that advances aircraft one interval at a time could be prohibitive. (Using a time slot of too large a duration would likely violate assumption A1 above.) Instead, we can examine straight line paths between designated waypoints in a pair-wise fashion and identify conflicts when they occur, placing each identified conflict in the appropriate graph G_{st}.

In determining conflicts between waypoints one simple way to determine conflicts between flight plans is to measure the distance between airplanes at certain discrete points in time. However, if the interval between these points in time is too large, a conflict may be overlooked. On the other hand, decreasing the interval size of each time period may render the problem too large to solve in an acceptable amount of time. To resolve this problem, we perform the following analysis for each pair of flight plans in order to detect if and when the conflict occurs.

Consider flight i at time t_a and let (x_a^i, y_a^i, z_a^i) represent its position at this point in time. We assume that from any discrete point in time to the next designated point in time, each flight traverses a straight line path. For example, if both flights i and j being examined for potential conflicts traverse straight line paths between certain designated fixes or way-points, then by defining the discrete points in time as the union of the various times that each flight would reach each of its respective way-points, we would have this assumption holding true. Accordingly, the direction vector d_i for the flight i during the time interval $[t_a, t_{a+1}]$ is determined as follows:

$$d_i = (d_x^{\,i}, d_y^{\,i}, d_z^{\,i}) = (x^i_{a+1} - x_a^{\,i}, y^i_{a+1} - y_a^{\,i}, z^i_{a+1} - z_a^{\,i}) \tag{18}$$

The position of i at any point t’ t' $[t_a, t_{a+1}]$ can be estimated as being given by

$$(x_a^i + d_x^i \;\; t, y_a^i + d_y^i \;\; t, z_a^i + d_z^i \;\; t) \text{ for } 0 \le t \le 1 \text{ where } t \equiv \frac{t' - y_a}{t_{a+1} - t_a}$$

The same analysis can be used to describe the trajectory of flight j during the interval $[t_a, t_{a+1}]$.

We now wish to find the minimum distance between flights i and j during the interval $[t_a, t_{a+1}]$. This minimum distance will be used to determine if the two flight plans under consideration are conflicting. Define the *interference domain* if radius r_i as flight i’s surrounding airspace, and c_i as the circumscribing sphere surrounding i. Flights i and j would be in conflict if the minimum distance separating flights i and j is lesser than max $\{(r_i + c_j), (r_j + c_i)\}$. The distance D(i,j) between flights i and j can be calculated as follows.

$$\begin{aligned} D(i, j) = {} & [(x_a^i + d_x^i \;\; t) - (x_a^j + d_x^j \;\; t)]^2 + [(z_a^i + d_z^i \;\; t) - (z_a^j + d_z^j \;\; t)]^2 \\ & + [(y_a^i + d_y^i \;\; t) - (y_a^j + d_y^j \;\; t)]^2 \end{aligned} \tag{20}$$

The minimum distance can be found by setting the first derivative of this expression with respect to t equal to zero and solving for t. Let t* be the solution thus obtained. Since the paths of these flights are linearly estimated, then

$$t = \begin{cases} 0 & \text{if } t < 0 \\ t & \text{if} 0 \le t \;\; \le 1 \\ 1 & \text{if } t \;\; > 1 \end{cases} \tag{21}$$

The resulting value of t* can now be used to calculate the minimum distance separating the two flights during the time interval $[t_a, t_{a+1}]$. If this distance is smaller than the minimum distance established for a conflict, the time interval over which these two flights are in conflict can be computed, and the sector(s) in which these conflicts occur could be determined. An edge between i and j is accordingly entered into the appropriate conflict graphs.

An airspace planning model, AP1, can now be constructed that incorporates the workload and the conflict constraints, along with suitable costs in the objective function, as stated below.

$$\text{AP1: Minimize } \sum_{i \quad M}\sum_{p \quad P_i} c_{ip}x_{ip} + \sum_{s \quad S}\sum_{n=1}^{\bar{n}_s}\mu_{sn}y_{sn} + \mu_e(x_u^e - x_l^e) + \mu_u^e x_u^e \tag{22a}$$

$$\text{subject to } \sum_{p \quad P_i} x_{ip} = 1 \qquad i \quad M \tag{22b}$$

$$\sum_{(i,p) \quad C_{sk}} x_{ip} - n_s \le 0 \qquad k, \quad , K_s, s \quad S \tag{22c}$$

$$x_l^e \le \sum_{(i,p) \quad A_f} \alpha_{ip}x_{ip} \le x_u^e \qquad k = 1, \quad , K_s, s \quad S \tag{22d}$$

$$n_s = \sum_{n=1}^{\bar{n}_s} n y_{sn} \qquad s \quad S \tag{22e}$$

$$\sum_{n=1}^{\bar{n}_s} y_{sn} \le 1 \qquad s \quad S \tag{22f}$$

$$x_P + x_Q \le 1 \text{ for all } (P, Q) \quad FC \tag{22g}$$

$$\sum_{p \quad S_k} x_P \le |S_k| - 1 \text{ for each pair } k \quad A_{st}, \quad t \quad H, s \quad S \tag{22h}$$

$$(x, y) \text{ binary}, x_l^e \ge 0, x_l^e \le n_e. \tag{22i}$$

Remark 7. We can alternatively model the conflict constraints by defining a variable z_{PQ} for each edge (P, Q) in the conflict graph, P < Q, which takes on a value of 1 if this conflict is permitted and 0 otherwise. Then, we would have a single conflict constraint for each sector x in period t that requires the sum of z_{PQ} over (P, Q) in A_{st} to be no more than 1. These z variables would then need to be related to the x-variables via the following constraints:

$$z_{PQ} \le x_P, \; z_{PQ} \le x_Q, \; z_{PQ} \ge 0, \; z_{PQ} \ge x_P + x_Q - 1$$

Note that this in effect would create a linearized version of essentially a quadratic model based on $z_{PQ} = x_P x_Q$, but it would permit the penalizing of different types of conflicts differently in the objective function. However, its LP relaxation will likely be weaker, although RLT can be used to strengthen it. A formulation for this alternative model AP2 is given below.

$$\text{AP2:}\quad \text{Minimize} \sum_{i \quad M} \sum_{p \quad P_i} c_{ip} x_{ip} + \sum_{s \quad S} \sum_{n=1}^{\bar{n}_s} \mu_{sn} y_{sn} + \mu_e (x_u^e - x_l^e) + \mu_u^e x_u^e \tag{23a}$$

$$\text{subject to} \sum_{p \varepsilon P_i} x_{ip} = 1 \qquad i \quad M \tag{23b}$$

$$\sum_{(i,p) \quad C_{sk}} x_{ip} - n_s \le 0 \qquad k, \quad , K_s, s \quad S \tag{23c}$$

$$x_l^e \le \sum_{(i,p) \quad A_f} \alpha_{ip} x_{ip} \le x_u^e \qquad f = 1, \quad , F \tag{23d}$$

$$n_s = \sum_{n=1}^{n_s} n y_{sn} \qquad s \quad S \tag{23e}$$

$$\sum_{n=l}^{\bar{n}_s} y_{sn} \le 1 \qquad s \quad S \tag{23f}$$

$$x_p + x_Q \le 1 \text{ for all } (P, Q) \quad FC. \tag{23g}$$

$$\sum_{(P,Q) \quad A_{st}} z_{PQ} \le 1 \qquad t \quad H, \quad s \quad S \tag{23h}$$

$$z_{PQ} \le x_P, z_{PQ} \le x_Q, z_{PQ} \ge 0, z_{PQ} \ge x_P + x_Q - 1 \tag{23i}$$
$$(P, Q) \quad A_{st}, \quad t \quad H, x \quad S$$

$$(P, Q) \quad A_{st} \quad (t \quad H) \text{ and } \quad (x \quad S) \tag{23j}$$

$$(x, y) \text{ binary}, x_l^e \ge 0, x_u^e \le n_e. \tag{23k}$$

Remark 8. For sectors that are unable to handle even one conflict over the defined duration of a single time slot, we can examine the union of the graphs over more than one time slot, as necessary, and impose conflict constraints with respect to the resulting graph that represents conflicts over the expanded duration. This can accommodate the capabilities of different sectors differently, if necessary.

Remark 9. The principal value of this model would arise in providing insights into the problem situation via various what-if scenario investigations. For example, the following types of investigations can be considered.

(a) Alternative restrictions on the cordoning of airspace around the RLV spaceport during launches could be evaluated with respect to this model. Different airspace restrictions would yield different values of cost coefficients in (15) based on fuel and delay computations. In addition, one might develop certain measures of safety, and incorporate appropriate penalties in the objective cost coefficients to reflect the relative safety of trajectories with respect to RLV operations. This can be particularly accomplished when treating n_{sk} as variables n_s as in (15').

(b) The effect of various ATC policies can be evaluated with respect to their influence on the parameters n_{sk} in constraints (15c). ATC workload restrictions (and/or costs) can also be reflected via the parameters n_{sk} along with their associated costs (when treated as variables in (15’)).

(c) The effect of alternative flight plans can also be evaluated using this model. In fact, this model can itself serve to evaluate the efficacy of various flight plan generation programs. Also, this model can be used in conjunction with SIMMOD/RAMS, which are large-scale simulation models for analyzing airspace operations related to a given set of flight plans. Hence, RAMS and SIMMOD can be used to provide a more detailed evaluation of a solution prescribed by our model.

(d) Similar to (b), different regulations imposed by FAA might yield different interpretations on what poses a “conflict.” These policies could be evaluated by translating them into appropriate constraints of the type (15c) and examining their effect on the model solution.

In summary, this model can be utilized in one of two ways.

(a) **Generator of a suitable mix of flight plans** for a set of flights operating in the vicinity of a spaceport: In this role, the model can be coordinated with SIMMOD/RAMS by using the latter simulation package to evaluate in more detail the airport operations related to the prescribed solution suggested by the model.

(b) **Policy Evaluator:** Various what-if scenarios can be evaluated by policy/decision makers in determining operational guidelines.

Hence, the model can be used, both in a tactical decision-making mode, as well as for generating strategic plans.

3.5 Implementation of Simulation/Optimization Model

A computer simulation and optimization model has been implemented in Phase I to assess minimum impacts of RLV operations in NAS operations. This model uses aircraft flight plan data, ATC restriction and general ATC sector databases.

3.5.1 Sectors and Flight Plans

Sectors are defined in terms of sub-sectors which are convex polyhedra in shape. The sub-sectors are bounded by vertical and horizontal hyperplanes in three dimensional space. The user defines the sub-sectors in terms the extreme points of the horizontal hyperplane and the top and bottom ceiling as explained before. The sectors and the sub-sectors may be stacked one over the other or may be staggered in any plane.

The user can input different probable alternative flight plans for a given pair of origin and destination. These alternatives may vary with respect to the departure time (deviated within a tolerable range from the preferred departure time), cruising altitude, and proposed cruising mach number. While cruising altitude separates the alternatives spatially, the departure time and cruising mach number spaces the alternatives in the time domain.

3.5.2 Model Inputs

A computer program has been developed to generate the constraint equations and the cost coefficients for the airspace planning model AP1. An analytical, dynamic and deterministic simulation model has been developed in Matlab 5.1 that is compatible with UNIX, DOS and MacOS operating systems. The user is required to input the sector information and the flight schedule in the respective input files.

In order to handle the nonconvexity associated with the sectors, the nonconvex sector should be divided into convex sub-sectors. The sectors are defined in terms of these sub-sectors in the file **Main_sect.in**. Sub-sectors are defined in terms of the nodes that form their vertices and in terms of their upper and lower ceiling altitudes. The nodes associated with each sub-sector are defined in the input file **Sub_sect.in** and the corresponding ceilings are contained in file **Sect_height.in**. Coordinates of the sector nodes are defined in terms of the latitude and longitude in the file **Node.in**.

3.5.3 Flight Plan Information

The information regarding the flight schedule should be defined in the input file flt_schd.in. The user should define the flight plan number, the alternative number for that kind of flight plan (in order to distinguish between alternatives), the name of the airline, the flight model, the temperature above ISA (International Standard Atmosphere i.e 25^{o}C), the origin and destination airport, the cruising altitude, the cruising mach number, the takeoff weight (in thousands of pounds) and the departure time in hours and minutes. Table 3-1 contains a sample flight plan input file.

To illustrate the use of input flight plan data refer to Table 3-5. The second row in Table 3-1 applies to flight plan for flight trip 1 and alternative number 2. The flight belongs to airline AA, the aircraft type is a heavy twin engine aircraft departing at 500,000 lb. The flight departs Miami International (MIA) for Dulles International Airport (IAD). The flight cruises at altitude 31,000 feet at Mach 0.8. The departure time is 10:15 A.M.

The model is currently being modified to accept ETMS data obtained from real aircraft tracks in NAS. Further enhancements are being made to predict flight costs for a larger aircraft data set. The European Bada data set is being look after as possible source of fuel burn information.

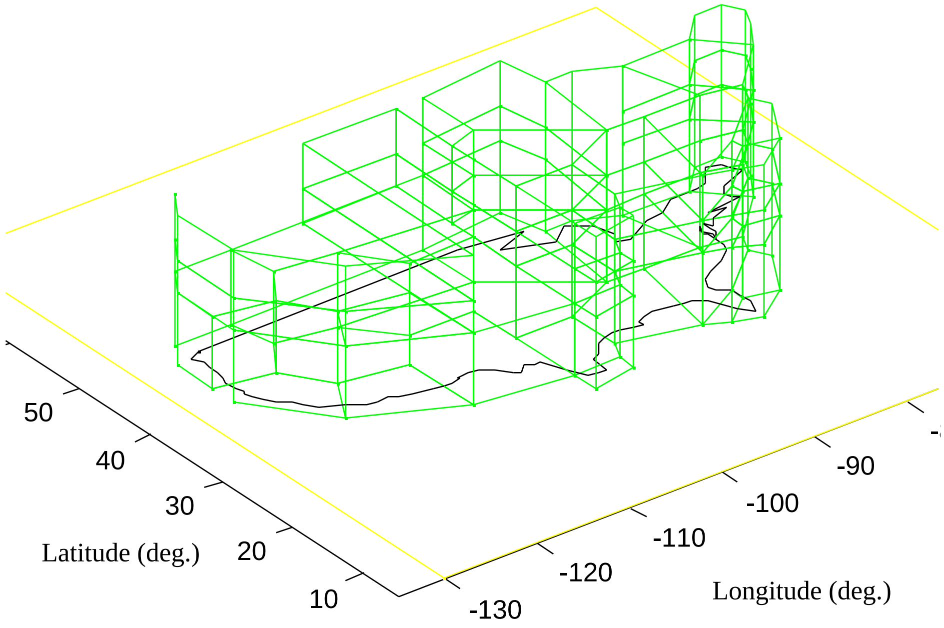

Figure 3-5: Sample Airspace Sector Representation

Table 3-1: Sample Flight Plan Data Input File

Trip #	Alternative #	Airline	Model	ISA+ Temp (^{o}C)	Origin	Destination	Altitude	Mach	DTW (klb)	Dep. Time (hr)	Dep. Time (min)
1	1	AA	twn_eng	0	MIA	IAD	40	0.8	475	10	00
1	2	AA	twn_eng	0	MIA	IAD	30	0.65	500	10	15
1	3	AA	twn_eng	0	MIA	IAD	35	0.72	480	10	00
1	4	AA	twn_eng	0	MIA	IAD	30	0.72	500	09	45
2	1	AA	F100	10	DFW	MIA	30	0.65	85	08	00
2	2	AA	F100	10	DFW	MIA	30	0.65	90	07	55
2	3	AA	F100	10	DFW	MIA	30	0.73	85	08	10
2	4	AA	F100	0	DFW	MIA	30	0.75	90	08	15

3.5.4 Flight Cost Estimation

The cost of a flight plan, F_{cost}, is estimated based on the fuel consumption and the time of travel in the airspace network. The travel time is compared with the minimum possible traversal travel time from the origin to a destination at the given speed. Any additional time required adds an extra cost to the flight plan. The following equation is used to estimate and aircraft flight plan cost.

$$F_{cost} = d \times sf \times fc \times DOCF + \left[TT - TT_{min}\right] \times ct \tag{24}$$

where:

d is the total flight distance (spherical coordinates), sf is the specific fuel consumption which varies with the crusing mach number, cruising altitude, temperature characteristics. The implementation of specific fuel is done for different aircraft models by coupling an independent fuel consumption model. In equation (24) fc is the cost of fuel (assumed to be 0.3$/kg for preliminary evaluation), $DOCF$ is the Direct Operating Cost Factor assumed to be 2.5 in the model, TT is the travel time under nominal traffic conditions, TT_{min} is the minimum possible travel time between the origin and the destination at the given speed and ct is the cost of time assumed to be 500$/hr in our intial simulation runs.

3.5.5 Flight Plan Generation

The program developed generates flight paths between a given set of origins and destinations. The flight path is generated according to the minimum globe-circle route between the origin and destination at the given cruising altitude. Based on the aircraft model, the temperature conditions at the departing airport, the takeoff weight, the cruising altitude, and the mach number, the climb profile of the flight is generated. The model uses a digitized flight characteristics database that is available for this purpose. The model will detect any infeasible flight plan and will issue an error message regarding any flight plan that is not feasible. A flight plan may be infeasible for one of the following reasons.

1) The flight is unable to climb to the specified cruising altitude for the given takeoff weight.
2) The destination airport is too close for the flight to be able to climb to the specified cruising altitude before reaching the destination.
3) The flight is unable to cruise at the specified mach number.
4) The takeoff weight exceeds the maximum allowable takeoff weight.

Five representative way-points are generated for the climb profile. In the cruising segment of the flight path, the way-points are equally spaced apart. The descent phase is considered to be the last 100 miles of the flight trajectory. For the calculation of way-points in the cruising segment, spherical coordinate geometry formulas are used to realistically simulate an aircraft path in the airspace.

3.5.6 Model Operational Features

The program stores the adjacency information of the sectors defined with respect to the nodes, vertical, and the horizontal faces. For each flight plan, the way-points are generated as described before.

3.5.7 ATC Workload Constraints

Starting at the initial point in a time horizon H, the program proceeds in the direction of the flight path from one sector to sector, making use of the adjacency data of the sectors. Thus, for each flight plan, the sectors through which the flight passes and the time during which it passes through the sectors are stored. For each sector, the flight that traverses through it and the time at which it crosses the sector are stored. This information is used to assess the maximum overlapping subset of flights occupying the sectors at any give time in order to generate workload constraints.

3.5.8 Conflict Constraints

Conflict constraints are generated comparing each flight plan with all other flight plan alternatives over time and detecting potential conflicts. After detecting potential conflicts, the workload constraints may are updated because a flight will impose a workload on a sector even if it is not passing through that particular sector, in case it conflicts with a flight passing through that sector. This scenario is illustrated in Figure 3-6.

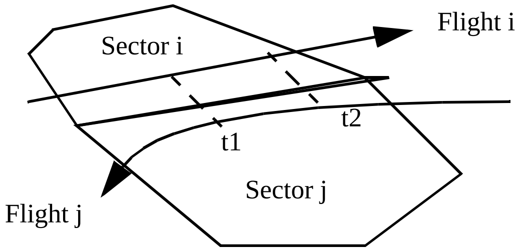

Figure 3-6: Workload Imposed by Conflicting Flight Plans

Flights i and j are in conflict from time t_1 to time t_2. Flight i passes through sector i and Flight j passes through sector j. Since Flights i and j are in conflict, the Flight j is considered to impose workload on sector i from time t_1 to time t_2, even though it never flies across sector i. Similarly, Flight i imposes workload on sector j from time t_1 to t_2. Once all the potential conflicts are identified, the workload constraints are modified to include additional workload imposed by all conflicting flights.

3.5.9 Objective Function

The objective function consists of the cost of the flight plan and the cost of handling workload by a sector. The workload cost will be an input by the user, and the cost of each flight plan is estimated by the program according to equation (24).

3.5.10 Detouring Around Special Use Airspace

Since the main goal of the program is to consider blocked sections of airspace representing RLV operational scenarios an algorithm to reroute aircraft has been developed. In order to determine the flights flying across the Special Use Airspace (SUA), the program is first run considering SUA only. If a flight happens to pass through the SUA during the blocked time, a detour in the flight path is considered. The modified flight paths are used to generate the sector workload and the conflict constraints. The SUA is considered to be convex polyhedron in shape.

If the flight passes through the SUA during the blocked time, a checked is made to verify if holding the flight in a sector before it enters the SUA is a viable alternative (i.e. saves time). The outcome of this procedure is compared with the shortest detour path.

If the detour takes place, two detour alternatives are considered. One of them will be the shortest detour and the other will be the detour around the SUA in the opposite way as shown in Figure 3-7. It may so happen that the longer detour may turn out to be a better alternative when the interaction within the overall system are considered. Hence a flight needing detour will trigger an additional flight plan (variable) in the optimization model.

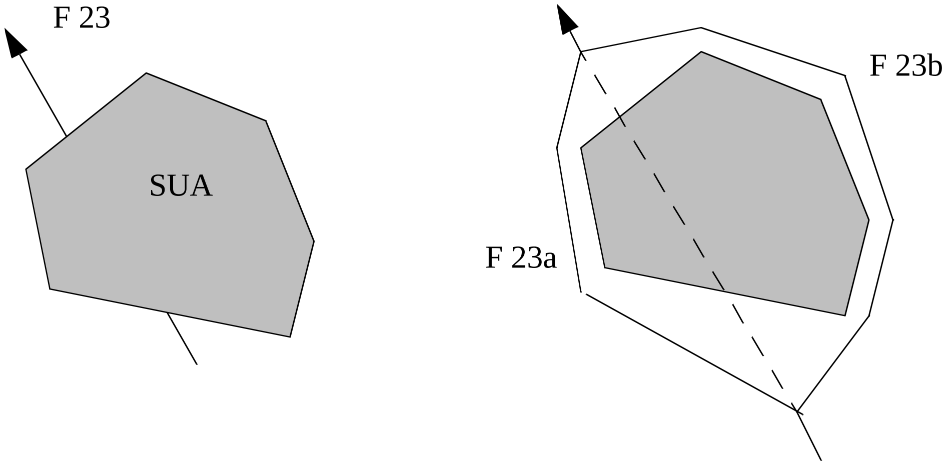

Figure 3-7: Possible Detour Paths

3.5.11 Computer Model Sample Output

The output of the program is the objective function, the workload and conflict constraints to be used by the optimization model. The following paragraph describes a sample file to illustrate the mechanics of the modeling procedure described in Sections 3.4 and 3.5.

The program was executed for the case considering the detour of flights around the Kennedy Space Center (KSC). Six flight trips were considered. Each trip has four alternative flight plans. Table 3-2 illustrates all flight plans considered. The flight paths and the sector geometry have been shown in Figures 3-1 and 3-2.

Table 3-2: Flight Schedules for Case Study

Trip #	Alter native #	Airline	Model	ISA+ Temp (^{o}C)	Origin	Destinati on	Altitude	Mach	DTW	Dep Hr	Dep Min
1	1	AA	twn_eng	0	MIA	DCA	40	0.8	475	10	00
1	2	AA	twn_eng	0	MIA	DCA	30	0.65	500	10	15
1	3	AA	twn_eng	0	MIA	DCA	35	0.72	480	10	00
1	4	AA	twn_eng	0	MIA	DCA	30	0.72	500	09	45
2	1	AA	F100	0	DFW	MIA	30	0.65	85	08	00
2	2	AA	F100	0	DFW	MIA	30	0.65	90	07	55
2	3	AA	F100	0	DFW	MIA	30	0.73	85	08	10
2	4	AA	F100	0	DFW	MIA	30	0.75	90	08	15
3	1	AA	twn_eng	0	BGR	MIA	36	0.65	450	07	30
3	2	AA	twn_eng	0	BGR	MIA	40	0.8	450	07	25
3	3	AA	twn_eng	0	BGR	MIA	40	0.73	450	07	20
3	4	AA	twn_eng	0	BGR	MIA	33	0.75	450	07	00
4	1	UAL	twn_eng	0	MIA	JFK	30	0.7	475	10	00
4	2	UAL	twn_eng	0	MIA	JFK	40	0.65	475	10	15
4	3	UAL	twn_eng	0	MIA	JFK	35	0.74	475	10	15
4	4	UAL	twn_eng	0	MIA	JFK	30	0.8	475	10	15
5	1	UAL	twn_eng	0	MIA	EWR	35	0.7	500	10	00
5	2	UAL	twn_eng	0	MIA	EWR	40	0.65	500	10	00
5	3	UAL	twn_eng	0	MIA	EWR	35	0.72	500	9	45
5	4	UAL	twn_eng	0	MIA	EWR	40	0.8	500	10	15
6	1	UAL	F100	0	RDU	MIA	28	0.65	85	09	00
6	2	UAL	F100	0	RDU	MIA	28	0.65	90	09	15
6	3	UAL	F100	0	RDU	MIA	28	0.73	85	09	00
6	4	UAL	F100	0	RDU	MIA	28	0.68	85	08	45

The above problem formulation was fed into CPLEX-MIP 3.0 (linear & mixed-integer programming software) and the following optimal solution was obtained.

Flight plans selected : x14, x21, x31, x42, x52 and x64.

Minimum cost of operating these selected flights : $33,203.
Maximum ineffective measure: 50
Equity disparity among airlines:0.

3.6 VPI Phase II Plan

The main topics to be addressed in Phase II of this study are:

a) Detailed analysis of KSC and Edwards A.F. B. operations. A database of 7 launch days has been requested from Air Traffic Services at the FAA to analyze aircraft operations around spaceports during and after space vehicle launches and reentry phases. This baseline database will be used to impacts under the current operational procedures and then predict possible impacts of RLV operations once Free Flight is commonplace in NAS in the year 2005. This work is currently starting at VPI with RAMS and SIMMOD.

b) Application of optimization model to KSC and Edwards A.F.B. scenarios. This particular topic is important to demonstrate the possible pro-active approach that FAA and airspace users could take to better integrate RLVs into the future ATC system.

c) Estimation of FAA infrastructure costs to support RLV operations. While heavy emphasis is usually taken in previous studies on the subject to quantify user costs due to RLV disruptions our approach looks at the possible ramifications of RLV integration from the airspace service provider perspective as well.

d) Estimation of non-user costs/benefits. This is an activity that has not been quantified in any study and deserves serious consideration. AS the number of launches increases in the near future more and more commercial space service providers need to be considered to understand the benefits

References

1) “Commercial Pegasus Payload User’s Guide 3.0”, October 1, 1993, Orbital Sciences Corporation.

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3) “Eastern and Western Range, Range User Handbook”, EWR 127-1, 1995, Range Safety Office, Patrick Air Force Base, FL 32925-3238.

4) “7400.2D Procedures for Handling Airspace Matters”, Sept 16, 1993, Federal Aviation Administration, Washington, DC.