Integration of Reusable Launch Vehicles into Air Traffic Management

Phase II

MIT Research Final Report

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Preface

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This document is based in part on the Master of Science Thesis of Kashif Khan, “Air Traffic Management and Conflict Analysis for Reusable Launch Vehicles”, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, September, 1998 [18].

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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., Orbital Sciences Corporation’s 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, the Massachusetts Institute of Technology (MIT) and Virginia Tech (VT) undertook a multi-part study as part of the National Center of Excellence for Aviation Operations Research (NEXTOR). The goal of this study was to identify the critical issues that need to be addressed, the tools that could be used to address them, and to develop recommendations for incorporating RLVs into Air Traffic Management. MIT focused on RLV mission profiles and modes of utilizing airspace, and VT focused on identifying models and methods to quantify and optimize costs of RLV operations in the National Airspace System (NAS).

This document reports the results of Phase II of the MIT part of the effort. Phase I results are summarized in Ref. 19.

In Phase II, MIT efforts focused on developing a model to determine the required Alert Zone size for an RLV, based on parameters such as encounter geometry, velocity, maneuvering authority, and uncertainties in current and projected trajectories. Based on this model, the time or distance between RLVs and conventional aircraft at which conflict resolution action would be required can be determined. This report discusses the development of the model and provides several parametric studies showing the impact of the RLV performance parameters on Alert Zone size. Conflict avoidance options using measures of Alert Zone size and deviation from track were compared. Preliminary analysis of required traffic deviation as a function of heading uncertainty was used to compare SUA to tactical conflict resolution for head-on conflicts. This allowed initial partitioning of when SUA is appropriate and when tactical separation is appropriate. For example, for equal speeds and uniform distributions of traffic, it was found that up to ±24° heading uncertainty could be accepted for tactical resolution before a 60NM diameter SUA became the more efficient solution.

Because the acceptability of tactical conflict management may hinge on operator performance and decision aiding capabilities, several recommendations for future human-factors studies are also made.

In future work (as part of a Phase III study), MIT will apply the model developed here in order to calculate the traffic delay, fuel, and workload impacts of operating in a tactical conflict detection mode. These data will then be compared against similar performance metrics determined at VT for more conventional SUA operations. The results provide requirements (in terms of vehicle performance, sensor accuracy, controller aids, and traffic density) that must be met in order to operate in a mode that is more tactical than conventional SUA.

1 Introduction

Since the beginning of the space age, 40 countries and international organizations have launched one or more satellites. As of June 17, 1998, 2,495 satellites of all kinds were in orbit around Earth, according to the U.S. Space Command [1]. An all-time record was set in 1997 with 150 payloads placed in orbit. The United States launched 68, Russia 50, Europe 19, China eight, Japan three, and India and Brazil one each [2]. More than 1200 satellite launches are planned for the next decade by civilian and other organizations [3, 4].

Because of recent advances in communications technologies, it is now possible to launch constellations of hundreds of communications satellites into low earth orbit (LEO). There are currently more than a dozen new low earth orbit mobile communications satellite networks in planning and development stages [5]. The Geosynchronous Earth Orbit (GEO) satellite markets are also undergoing rapid expansion with new services such as high power Digital Broadcast Systems (DBS), and Cellular Communications. The communications satellite replacement market and the second-generation communications satellite deployment market will also become more significant over the next decade. Communications satellites that are planned for launch during the next ten years will have relatively short lifetimes, an average of five years, and entire satellite constellations will have to be replaced every five to seven years. Consequently, the frequency of space launch and recovery operations will increase rapidly.

This increased demand for commercial utilization of space is a substantial driver for the development of new technologies to improve space vehicle economics. Reusable Launch

Vehicles (RLVs) have the potential to increase space launcher efficiencies far beyond those achieved by current systems, and once the basic technologies have been proven, their share in the launch market should increase rapidly.

Private enterprise in the space launch industry has been limited until the present, but is increasing, and should eventually overtake the share of 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. Simultaneously, safety must be maintained.

The future of the National Airspace System is currently under review through concepts such as free flight, which seek to leverage advancing technologies that will allow improved control of separation between vehicles. Advances in tracking, navigation, communications, and related technologies power these new concepts and it is worthwhile to examine what role they can play in streamlining the coexistence of aviation and space operations.

Current space operations occur at only a few sites in the world and are relatively infrequent. The existing US space launch sites are at Kennedy Space Center, FL; Cape Canaveral Air Station, FL; Wallops Island, VA; White Sands Missile Range, NM; Vandenberg Air Force Base, CA; Edwards Air Force Base, CA; and Kodiak Island, AK. Several commercial launch sites such as California Spaceport, Spaceport Florida Facility, Virginia Space Flight Center, and Alaska Spaceport will also be established, with launch pads for additional types of launchers at the existing sites. Many existing and proposed non-U.S. launch sites will also have increased operations.

Use of these facilities causes some increase in air traffic delays and workload, but as space launch and reentry operations increase, these costs will rise. Currently, activation of the Space Launch facilities such as Kennedy Space Center lasts for up to 3_ hours at a time. Although the launch itself lasts for only a few minutes, the early activation allows time for controllers to clear the airspace needed for launch operations [6, 7]. The number of flights affected depends upon the time of day, and aircraft traversing the area during these periods suffer deviations adding 8-10 minutes of flight time. The diverted aircraft have to be absorbed into the neighboring air routes, and the increased congestion leads to system-wide delays.

Unlike expendable launch vehicles that are typically non-recoverable once they leave the launch pad, RLVs will be designed for multiple missions with fail-safe modes allowing recovery to landing sites. New flexible procedures for short-notice reintroduction of RLVs into the air traffic system will hence be required to allow for the possibility of vehicle emergencies during launch, on-orbit, or reentry. Reexamination of the procedures through which air traffic is separated from RLV traffic is therefore necessary and new operational procedures and modes need to be found and evaluated.

Space operations and aircraft operations are currently separated by defining Special Use Airspace (SUA) for exclusive use of space operations, around the launch and recovery facilities, which forbid entry of unrelated aircraft during operations. The SUA geometry is determined by the expected operational airspace usage requirements for the Space Vehicle, and provides an excess buffer in space and time. The margins are expected to provide acceptable physical separation of the different operations, and guarantee the required safety level. Figure 1 shows the Kennedy Space Center Special Use Airspace sectors over the Atlantic Ocean.

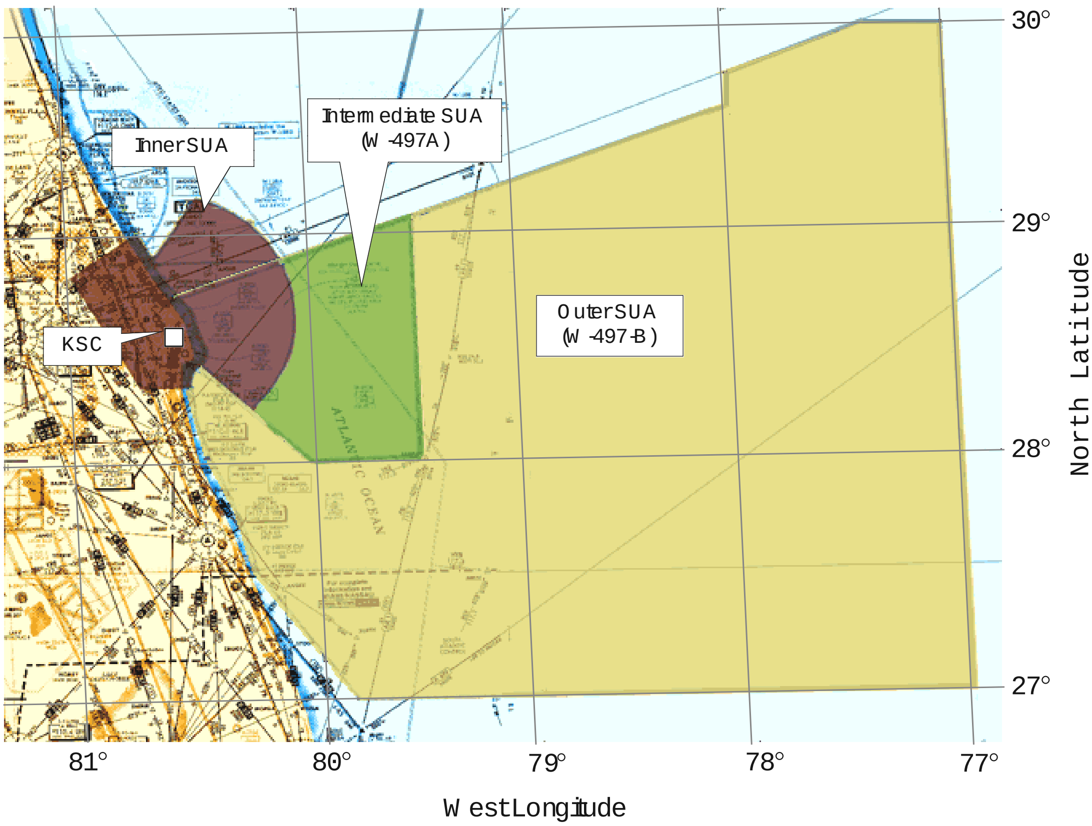

Figure 1: Kennedy Space Center Special Use Airspace

The current mode of operation transfers exclusive use of the SUA to space operations when requested. The SUA is depicted on aeronautical charts, and entry of all unrelated aircraft is prohibited when it is active. Activation of SUA therefore generates negative impact on air traffic flow depending upon its size, the usage requirements of conventional traffic, and the time of day and duration that it is in effect. The increasing frequency of space operations will cause greater impact on traffic in the National Airspace System. As effects on commercial air traffic increase, usage conflicts are likely to arise between the involved parties. It is therefore desirable to examine the potential for improving airspace utilization during space operations. Options such as mixed-mode airspace with tactical conflict resolution, where conventional and RLV traffic simultaneously use the same airspace, and are monitored and guided in real time, should be evaluated for benefits.

Each potential procedure or operating mode of airspace will entail requirements on technologies, equipment, and operator workloads. To determine whether a proposed concept is viable, these costs need to be balanced against the potential benefits of improved traffic flow and safety.

2 Background

2.1 RLV Characteristics

Many RLV designs are in the concept and development stages. The major current and planned space launchers are listed in Table 1. A number of other studies not listed here are also underway. Current space vehicles are all vertically launched (VT) from launchpads, with the exception of Pegasus, which is an example of Horizontal Takeoff (HT) vehicles that are launched from horizontal runways. Similarly the landings may be classified according to whether they are horizontal (HL), as for the space shuttle, or vertical (VL) as for the DC-X. We include parachute-assisted landings in the VL classification, as a significant horizontal component of velocity is not always present.

Launch vehicle performance characteristics are markedly different from conventional aircraft, as their mission objectives are different. However, for some of the proposed RLVs in Table 1 there may be certain phases of flight with similarities to conventional flight.

Table 1: Space Vehicle Types [8]

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

ELV: Expendable Launch Vehicle
SSTO: Single Stage To Orbit

VT: Vertical Takeoff
VL: Vertical Landing

HT: Horizontal Takeoff
HL: Horizontal Landing

Flight Phases

Any RLV mission is composed of a number of flight phases (Figure 2). Multi-stage vehicles will have some phases occurring in parallel. For example, jettisoned stages will return to earth while the vehicle continues its ascent. Definitions of phases of flight are listed in Table 2.

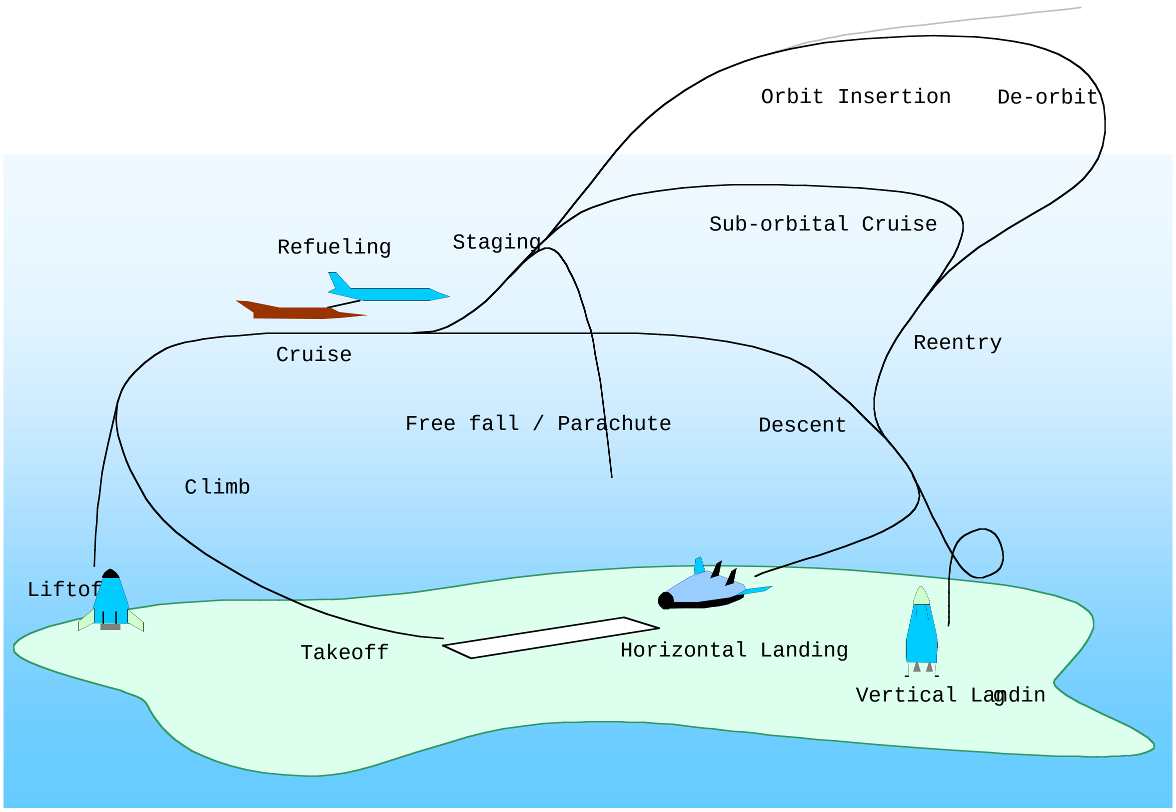

Figure 2: RLV Flight Phases

Table 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 significant positive vertical velocity component
Cruise	Flight at constant altitude or near-zero vertical velocity com
Staging	Deliberate 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
De-orbit	Removal from orbit, into re-entry trajectory
Re-entry	Entry from space Into the atmosphere
Descent	Flight with significant negative vertical velocity component
Horizontal landing	Conventional, aircraft-type horizontal recovery on a runway
Vertical landing	Near-vertical recovery, parachute or powered

Although the Takeoff, Climb, Cruise, Descent, and Horizontal Landing phases are functionally similar to conventional air operations, the velocities and accelerations may be extreme in comparison. In addition, vehicle maneuverability beyond the nominal mission profile may have severe limits. While many of the RLVs may be able to perform maneuvers for conflict avoidance, such maneuvers may put the completion of the mission at risk, and may cause loss of vehicle in the worst case. The result is that, at least initially, RLVs cannot be expected to perform avoidance maneuvers, and conventional aircraft alone will have to maneuver to resolve conflicts.

As an example, Figure 3 shows a typical unpowered landing profile of the space shuttle (STS) [9], compared to a 3° conventional descent profile. The Shuttle descends at vertical rates ranging from 20,000ft/min at 60,000ft to 11,000ft/min at 10,000ft, as compared to aircraft that are typically limited to ±4000ft/min. A typical descent is composed of a high speed, high altitude straight track segment from 80,000ft altitude, and then a 270° descending left turn segment to touch down as shown in Figure 4. The descent from 80,000 ft to touchdown takes approximately 6 minutes.

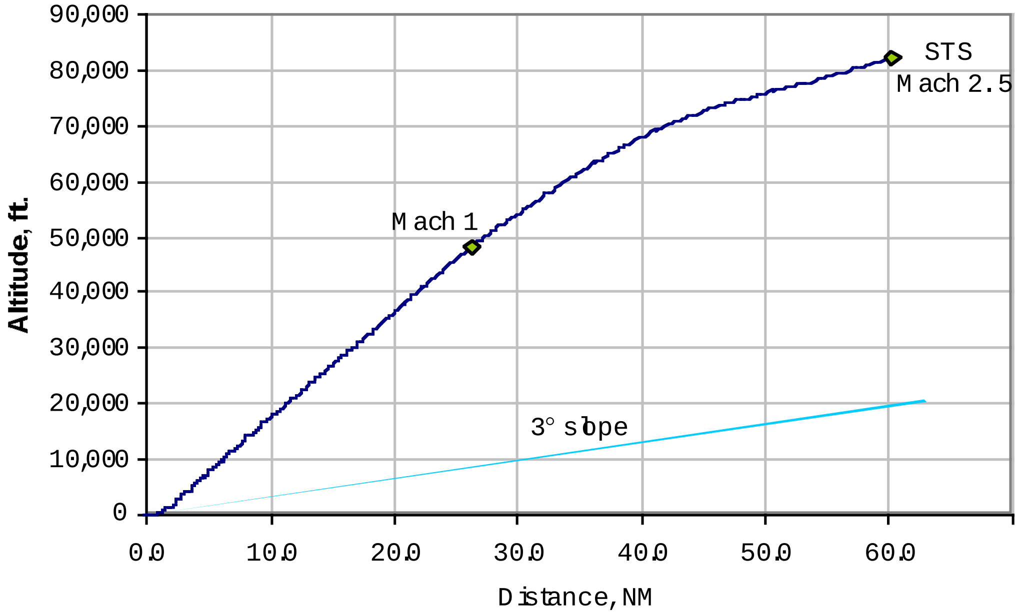

Figure 3: Space Shuttle Descent Profile [9]

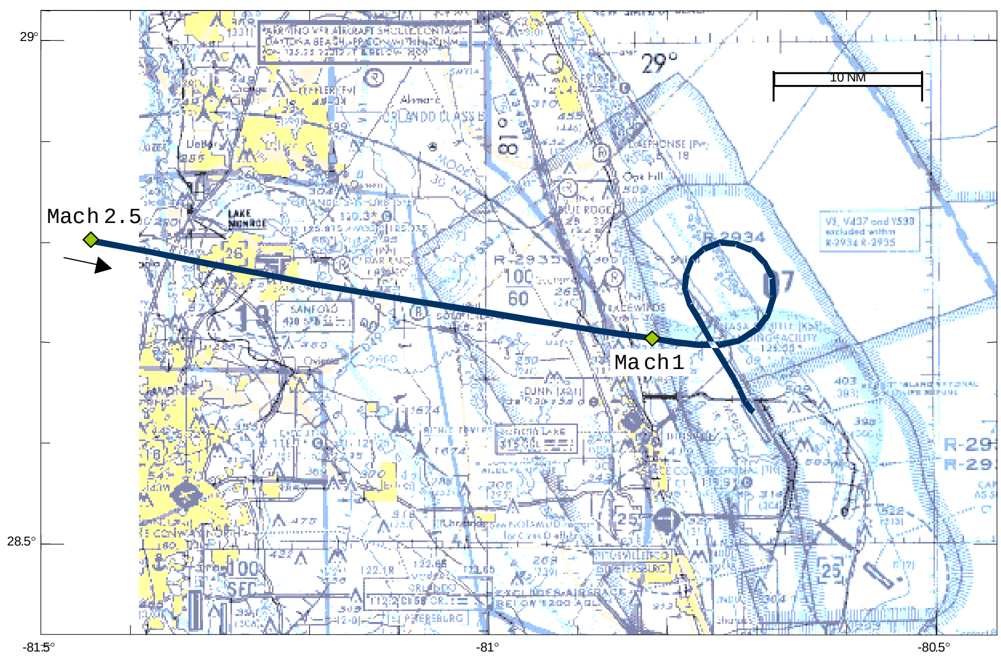

Figure 4: Space Shuttle landing track overlaid on Kennedy Space C
Region [9]

2.2 Air Traffic Control Issues

Air Traffic Control (ATC) Systems provide separation assurance and traffic management functionality in the National Airspace System. How airspace is defined and used reflects the mixing between tradition and technological capabilities. The choice of operating mode determines a balancing point between competing demands. Any concept used will impact both air traffic flow and the ability of the competing operations to be performed when needed. With each concept, there are vehicle and ground equipment requirements, and safety and operator workloads will be affected. All these considerations should be considered together when examining future airspace concepts, because improving a single metric can negatively impact the others.

Traffic separation providing adequate safety margins is achieved by a number of control methods and procedures. To achieve the required safety, and provide protection against failure, control systems and procedures are layered whenever possible to provide redundancy, and are often at work simultaneously. Wide variation in the degree of control from the ground is exercised, ranging from aircraft that self-separate visually, to those that are actively ground vectored. While examining the available options, the safety level must be maintained. Absolute safety level as a function of probability of conflict is difficult to determine, as it is dependent upon many interrelated factors. It is possible however, to make reasonable comparisons for changes in one component variable such as altitude separation or horizontal separation.

Safety separation requirements may be defined in terms of distance or time. The amount of separation that provides acceptable safety depends on many factors, as shown in Figure 5.

Available technology drives the sensor capabilities and vehicle maneuverability characteristics. Safety standards evolve along with operational experience. These factors allow evolution of separation standards, operating rules, and airspace structure, which then determine the amount of traffic the system is able to carry.

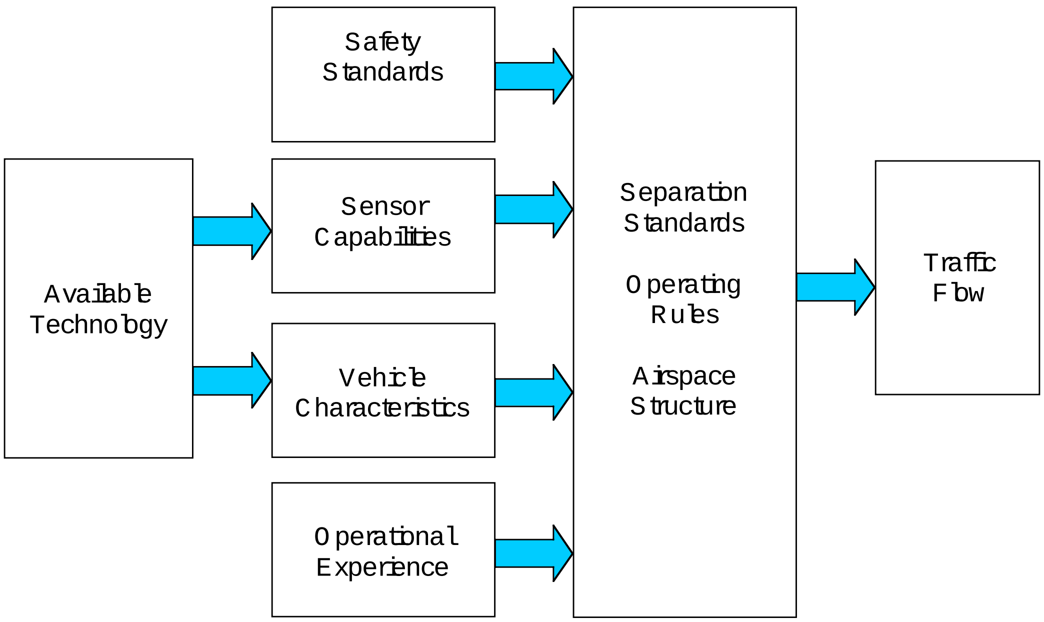

Figure 5: Airspace Traffic System Drivers

Several additional factors will influence the required safety buffer size for RLV operations. RLVs will have relatively large along-track accelerations. The exhaust from rocket engines may be hazardous, and expended stages and auxiliary operations such as refueling and chase planes may be present. The potential for catastrophic failure of a space vehicle is currently many orders of magnitude larger than for conventional aircraft operations, although it should decrease significantly with increasing operational experience. The uncertainties in these factors, especially the relatively high potential for catastrophic failure, account for the current need for large safety buffers around RLV and other space launcher operations.

As aircraft spend the major proportion of time cruising at constant altitude, and reliable altitude sensors are available, the current air traffic system is built around stratified flight levels. The controllers are given a two dimensional view of traffic on Planform View Displays (PVDs) with identification labels showing additional information such as altitude [14]. Typical Radar update rates are 12 seconds en-route and 4 seconds in the terminal areas. As discussed above typical aircraft vertical rates range between 1,000 - 2,000ft/min, with 4,000ft/min as an extreme. RLVs will in general have significantly larger vertical ascent rates during launch, and landing descent rates may also be relatively high, as many of them will be unpowered and have inefficient lifting surfaces.

The 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. Overlap between the control methods is normal and desired.

2.3 Protection Zones

Protection Zones are safety buffers or margins between vehicles using airspace. Under standard operating conditions, an aircraft may never penetrate the Protection Zone of another. Protection Zones provide an alternate way of specifying the separation requirements. They can be defined in terms of horizontal separation, vertical separation, and time, or by measures combining some or all of these factors into a single function. Many notional methods exist to determine protection zone sizes, while determining the best one for a particular problem is not always straightforward. Horizontal separation requirements are based upon operational experience, available radar tracking scan frequency and accuracy, and response times of controllers and pilots, while vertical separation standards are generally based on available altimeter accuracy. It is difficult to establish criteria for “safe” aircraft-RLV separation as no applicable standard methods exist. However, conventional separation standards can still be used as baselines for comparison with other options. The current aircraft separation standards are 5NM horizontally, and 1000 ft vertically (2000 ft above 29,000 ft), and the cylindrical puck shaped protection zone defined by these distances is used in what follows to determine the alerting volumes. Separation standards and hence Protection Zone geometry is allowed to change depending on flight characteristics, operating mode, quality of available tracking, and traffic environment.

2.4 Current Aircraft-RLV Separation Methods

Currently, space operation and aircraft separation is achieved through Special Use Airspace (SUA), similar to that used for military operations, around the launch ranges. Large static spatial and temporal buffers between the domains are provided. Figure 1 shows the charted SUAs for the Eastern Launch Range (Cape Canaveral).

Typically, the airspace is active several hours before and a short time after the space operations occur. ATC is informed and controllers reroute air traffic around SUA. 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. The timing of SUA operation is determined so that it is early enough for Notices to Airmen (NOTAMs) to be communicated at preflight, especially for VFR aircraft. The Cape Canaveral SUA is typically activated about 3 to 3_ hours before operation begins. Unnecessary activation sometimes occurs if the operation is canceled or delayed after the NOTAM is issued.

The current launch vehicle SUA definition process involves a detailed study of the launch system requirements, capabilities, and risk factors [11]. The size of the SUA is determined by limiting the probability that the vehicle crosses the boundary to outside airspace to 1 in 10^6. During launch, the probable Instantaneous Impact Point (IIP) is continuously calculated using telemetry data, assuming an instantaneous propulsion loss, and displayed in real time to a controller on the launch monitoring consoles. The mission is aborted (typically self-destructed) should the IIP pass outside the boundary of the defined region.

2.5 Potential Modes of Operation

Potential modes of airspace use for RLV operations as identified in Phase I are listed briefly below, as a range of likely operating regimes. The concepts can be divided into SUA-type, centralized control, and decentralized control categories. These alternatives will need to be examined for their effects on safety and traffic disruption, in addition to effects on equipage requirements and workloads.

2.5.1SUA-type concepts

Using a static protection zone, rather than one moving with the vehicle, is practical when the total amount of airspace the vehicle needs is relatively small. This is the case for RLVs with steep climb and descent trajectories or looping paths, such as those used employed by the space shuttle. Three options can be distinguished:

USE CURRENT SPACEPORT SUA

Current Spaceports (Cape Kennedy, Vandenberg AFB, Edwards AFB, White Sands AFB, and Wallops AFB) will continue to operate for the foreseeable future. Keeping the SUA definition philosophy intact, new RLV flight facilities can be added as needed in geographically suitable locations, to accommodate increased RLV operations. Safety studies for new vehicle operations, to define any required modifications to the current SUA regions, can be performed and then charted.

MISSION-SPECIFIC SUA

Current SUAs are designed to accommodate the entire range of space operations from a spaceport. Subsections of the SUA could be designed to satisfy the launch requirements for a subset of the possible launches. Then, depending on the mission, the appropriate sub-section of the SUA is activated. Other procedures would remain the same as for the typical SUA, and the effective disruption of the airspace system is reduced.

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 activated. Actively controlled aircraft would be allowed into the SUA with clearance from the ROC. One concept is to operate the SUA with similar requirements to current Class B airspace, except that any aircraft could be denied entry by ATC if a space operation were occurring. All VFR aircraft would be required to have clearance for entry. During RLV operations, ATC would be notified of what airspace, including safety buffers inside the SUA would be needed for RLV operations. ATC would maintain communications with the ROC for expected RLV operation times, and any updates or changes in the operations. Then, as required, ATC would vector air traffic around expected RLV routes.

2.5.2 Centralized ATC concepts

These modes closely parallel traditional air traffic control practices for conventional aircraft, with suitable modifications to compensate for the differences in performance.

SPACE TRANSITION CORRIDOR

The ROC or the RLV itself communicates the 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 the case discussed earlier — air traffic is separated from a (moving) region of airspace rather than from another vehicle itself.

RLV AS A HIGH, OR NORMAL PRIORITY VEHICLE

The RLV is treated similar to conventional aircraft, with equivalent requirements (files a flight plan, obtains a departure clearance, etc.). However, for separation assurance, the RLV may be given higher priority or “right-of-way” over other air traffic. ATC has responsibility for separation and needs appropriate guidelines for detecting and resolving conflicts to account for the RLV.

Prioritization issues are more critical with RLVs as they often have tight launch windows and any delay or redirection might cause the operation to be cancelled. If aircraft are given lower priority than RLVs, flight delays and airlines' costs will increase. Vectoring the RLV around conflicts is possible if the RLV is maneuverable and if resolution doesn't impact the mission plan.

2.5.3 Decentralized "Self-Separation" concepts

These modes are similar to the proposed "free-flight" concepts, and aircraft and RLVs are expected to 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, as the RLV typically enters and exits airspace in a short time span, and the time available for decision making is more limited.

2.6 Comparing Modes

Many RLVs will 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, which may have a significant cruise/ferry phase of flight, during which speed and vertical rates 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. 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.

Many of these technologies are expected to appear in the next decade as new operational concepts such as “free-flight” are implemented. New tracking technologies, such as GPS, currently in limited use, are expected to become available generally. Communication technologies will also become much improved.

Currently, three broad modes of operation are under active study: Conventional SUA; Space Transition Corridor; and Tactical Control. In the Conventional SUA concept, the reserved airspace is fixed in space and aircraft are vectored strategically around it. In the Space Transition Corridor (STC) case, a smaller reserved airspace corridor (which may extend to space or which may extend only a few seconds ahead of the RLV) is monitored, and air traffic is vectored around the STC as needed. In the Tactical Control concept, aircraft and RLVs are vectored around one another in a similar manner to conventional aircraft conflict management, without the use of reserved airspace.

Fundamentally, in the SUA concept, vehicles are separated from a fixed zone of airspace, in the STC concept, vehicles are separated from a smaller, transient, mobile zone of airspace, and in the Tactical Control concept, vehicles are separated from each other. In practice, however, tactical control involves protecting aircraft from entering Protected Zones around each other; thus, there is no fundamental difference between STC operation and Tactical Control except for the scale of the protected airspace. In Tactical Control, this airspace is generally 5 nmi in radius and 1000 or 2000 ft high. With a STC, there may be a larger corridor that is defined, or the STC may be a smaller region similar to a conventional Protected Zone.

To determine the conditions necessary to allow operating modes other than those in use today, some fundamental issues need to be resolved. In the following chapters, a maneuver constraint based approach is employed to determine a rational methodology for comparing conventional and unconventional modes for RLV-Aircraft separation. To compare operating modes, avoidance maneuvers are proposed and the needed alerting zones are determined. Metrics for evaluating avoidance maneuver costs are developed and compared with those for conventional methods of RLV avoidance. Comparison between decoupled vertical and horizontal avoidance and their applicability to various encounter geometries is examined.

2.7 Literature Survey

A number of techniques exist for analyzing conflict detection and avoidance exist. Kuchar and Yang [10] performed a broad survey of modeling methods for conflict detection and resolution.

Analytic solutions for airborne collision avoidance were discussed by Morrel, [15], who compared the relative advantages of vertical and horizontal avoidance, and formulated graphical analysis methods.

Krozel et. al. [14] performed a wide ranging study of conflict detection and resolution methods. They performed deterministic and non-deterministic, 2D and 3D conflict detection analysis based on the penetration of the Protected Airspace Zone, and found alert zones based upon deterministic and probabilistic criteria. They analyzed heading or speed control maneuvers in the horizontal plane, and altitude control in the vertical plane, for tactical close-range and strategic far-range cases. They developed maneuver charts based upon maximizing the range at closest approach, indicating the turn directions, acceleration signs, or climb/descent rates that each aircraft should select for any arbitrary initial relative state for cooperative and non-cooperative tactical collision avoidance maximizing safety. They found it more economical in non-cooperative heading maneuvers to turn the aircraft to the backside of the non-cooperating aircraft, and for cooperative cases, better to let the faster aircraft bear more of the burden. They found speed control maneuvers ineffective as means of conflict resolution in terms of cost and range required. They showed that altitude maneuvers were more efficient than heading change maneuvers in terms of energy usage and time penalties, and were uniformly effective for all relative headings.

The objectives in this work were to determine the intruder and encounter characteristics that present difficulties in conflict avoidance. A method to develop Alert Zones was devised using a new analytical relative velocity approach that allows direct determination of deterministic and probabilistic Alert Zones in vertical and horizontal planes, based on the vehicle and intruder characteristics. The alert zone approach was extended with special emphasis on conflict avoidance for vehicles with dissimilar flight characteristics such as RLV vs. aircraft. The method was designed to be extensible and to allow comparison between multiple candidate maneuvers using geometric relations.

3 Conflict Avoidance

In this chapter we discuss how to formulate the spatial limits that conflicting aircraft may be allowed to approach before action needs to be taken. A conflict is defined as a projected violation of traffic separation requirements. A violation occurs when one vehicle penetrates the protection zone of the other vehicle. As uncertainties are present in the sensor information and the predicted path, whether a conflict will occur can only be known with some level of confidence.

Once the possibility of a conflict becomes significant, whether and when to initiate an avoidance maneuver has to be determined. A number of avoidance maneuver options may be available at any given time. However, as the encounter progresses, the relative merits of options may change, and the number available may decrease as the intruder approaches closer to the ownship. We can wait until the conflict probability becomes high enough that action is required, but not so long that the probability of successful avoidance becomes low. We must not wait until all options disappear.

If the uncertainty of the intruder can be bounded, it may be possible to design an avoidance strategy to safely resolve the conflicts for all the possible outcomes within the uncertainty range, and successful avoidance can be guaranteed. In other cases, avoidance cannot be fully guaranteed no matter what we do and the only option then is to choose an avoidance maneuver that minimizes the conflict probability.

Intruders can be classified according to their motion relative to the ownship. The motion may vary in its complexity, and as may be expected, increasing complexity of motion increases the difficulty of analysis. As a starting point, we assume nominally linear constant speed motion for both the intruder and the ownship. Simple linear motion allows comparatively simple solution of the equations of relative motion.

For each class of intruders with a particular velocity vector, a boundary called the Alert Zone is determined (Figure 6). This boundary defines the closest that the vehicles can be allowed to approach before an avoidance maneuver must be initiated to resolve the conflict. An intruder that approaches closer to the ownship than this boundary before the avoidance maneuver is initiated will violate the separation requirements even if the avoidance maneuver is performed. The geometry of this boundary depends on the characteristics of the intruder, such as speed and relative heading, those of the ownship, the available avoidance maneuvers, latencies in sensors, automation and humans, and the geometry of the protection zone.

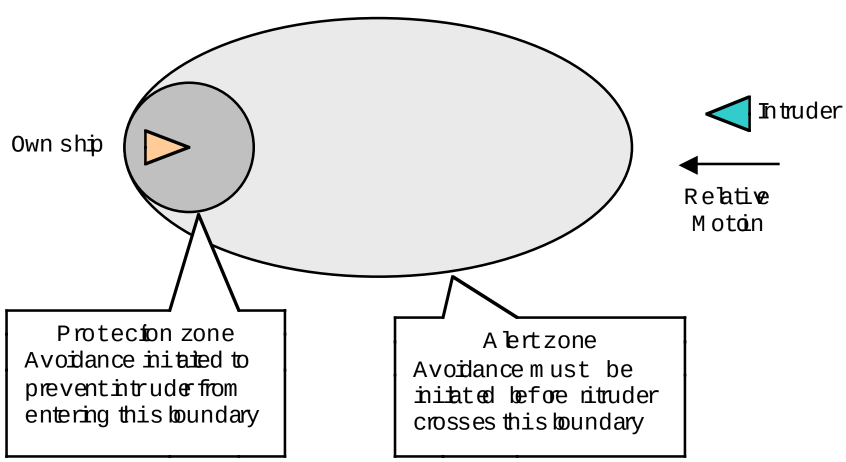

Figure 6: Alert Zone concept

3.1 Alert Zone Development

An Alert Zone is determined for each intruder based on an assumed set of avoidance maneuvers. To do so, we define a frame fixed on the intruder, and transform the motion of the ownship to this frame. Referring to Figure 7, the protection zone of the ownship following its nominal path sweeps a volume along a straight path in this space. An intruder that lies within this swept volume is projected to have a conflict with the ownship. To avoid such an intruder we require a different flight path, with a swept volume that does not include the intruder. This path is shown as a left turn in Figure 7. The alternate flight path and its swept volume move with the ownship following the nominal path. The alternate flight path must be selected before the intruder crosses into its swept volume.

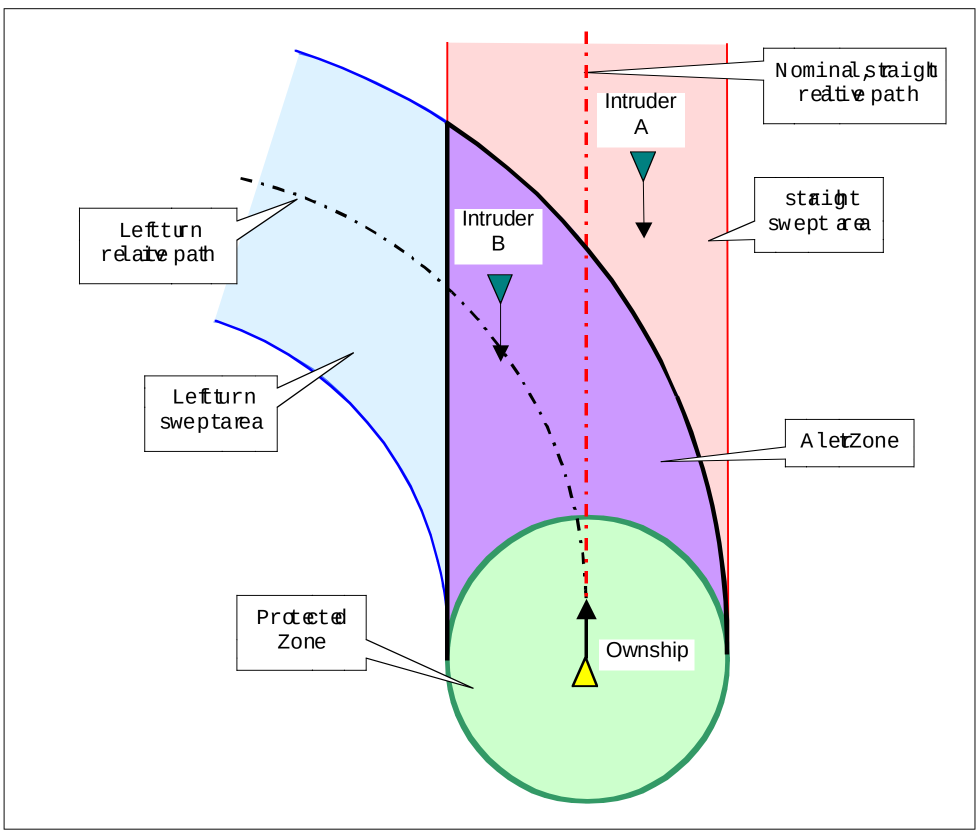

Figure 7: Alert Zone concept, Straight or Left Turn

In Figure 7, the intruders are approaching head on. Nominally, the ownship is following a straight path, but for example, a left turn from any point along it is available. Intruders A and B are in the swept area of the nominal straight path, and conflicts are projected with them. If a left turn were taken, a different volume would be swept as shown. It is possible to avoid A by turning left before it crosses the curved boundary of the Alert Zone. The latest we can delay turning is the boundary of the common volume between the two swept volumes. An intruder that crosses this boundary cannot be avoided using the assumed avoidance maneuver, as it would then lie within the area that both the options sweep. Intruder B has already crossed the boundary, and a protection zone violation by it is inevitable.

If we are allowed another option, such as a right turn, in addition to the nominal straight path and left turn, we get a different Alert Zone as shown in Figure 8. As the Alert Zone is now smaller than the one in Figure 7, we are able to avoid intruder B as well as A by taking the right turn.

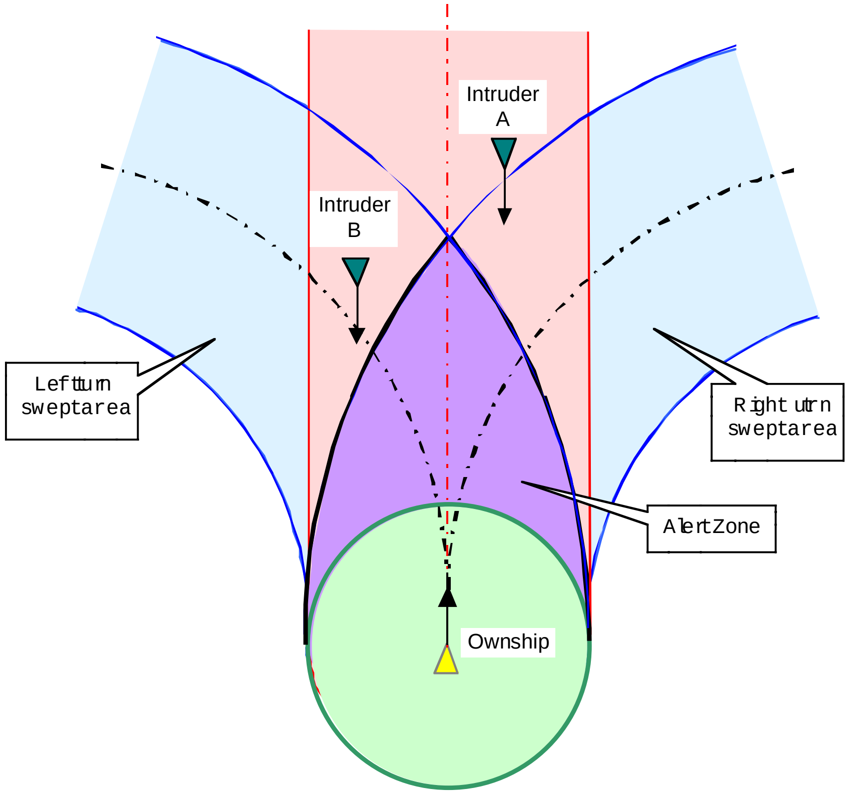

Figure 8: Alert Zone concept, Straight, Left turn or Right tu

The procedure outlined above is used to determine the Alert Zones using the swept volumes, and is described in detail in the Appendix. Alert Zones can be determined for horizontal avoidance maneuvers in the horizontal plane and for vertical maneuvers in a vertical plane, using the respective cross-sections of the protection zone. The Alert Zones for all classes of expected intruders can then be found and further analysis undertaken to optimize the avoidance strategy.

3.2 Avoidance maneuvers

An avoidance maneuver is used to achieve a displacement in space and time such that the separation requirements are fulfilled. Avoidance maneuvers can be made arbitrarily complex, and determining the optimal avoidance maneuver for a general conflict is a non-trivial problem.

We propose some simple candidate maneuvers that provide the required displacements directly, without proving that these are the best possible maneuvers. Then we can examine these for suitability, and substitute progressively complex maneuvers as needed to solve conflict scenarios that are inefficiently solved by the simple maneuvers.

Different constraints exist for vertical and horizontal resolution. The turning rates and vertical acceleration are limited by the allowable bank angles and load factors respectively. While there is no limit on the total turn angle, the vertical rates are limited. There are physical altitude limits, while in general, horizontal deviation is not similarly limited.

Avoidance maneuvers can be cooperative, where both vehicles take evasive action, or non-cooperative where only one does. Many RLVs are expected to have little capacity for maneuvering due to their performance limitations and mission requirements as mentioned earlier, and cooperative avoidance maneuvering will not be possible in most circumstances. In addition, when cooperative avoidance is used, issues involving maneuver synchronization and maneuver apportioning arise for vehicles with very different flight characteristics. Here, we take the simpler path and consider only non-cooperative conflict resolution, where the aircraft alone performs avoidance, and the RLV is assumed to be unable to deviate from its nominal flight path. As RLV capabilities increase in the future and greater margins for maneuvering become available, cooperative maneuvers should be considered to reduce individual penalties.

A horizontal avoidance maneuver may consist of the six phases listed below:

1. **Initial delay:** between detecting the intruder crossing the Alert Zone boundary, and starting the maneuver, to allow for automation, human, and aircraft response delays

2. **Turn Initiation:** by banking the aircraft from wings level to the maximum bank angle (e.g. 5 sec for 30° bank angle, [14])

3. **Turn:** at constant bank angle, such as 30° used hereon, giving a turn rate of 1.4°/second, until the required heading change is achieved

4. **Turn Termination:** by leveling the wings of the aircraft from the maximum bank angle (e.g. 5 sec for 30° bank angle, [14])

5. **Straight Travel:** once the turn is complete to the point of closest approach at when the resolution is complete

(Phases 1–5: Used to determine Alert Zone Geometry)

6. **Return to Original Heading or Original Track:** Depending upon which option is more desirable (e.g. Original Heading if flight destination is far away)

(Phase 6: Used for avoidance cost determination)

To simplify the analysis, phases 2 and 4 are absorbed into the delay (phase 1) and turn (phase 3). There is negligible impact on the Alert Zone geometry due to this simplification, as the duration of these transient phases is small relative to the others. These components of avoidance maneuvers are described in more detail in the Appendix.

The geometric analysis of conflicts is complex as the functions relating the quantities are transcendental and not suitable for purely analytical treatment. A suite of computational tools was developed as an aid to understanding the interrelationships of some of the important factors in conflicts and their resolution. A condensed schematic is shown in Figure 9.

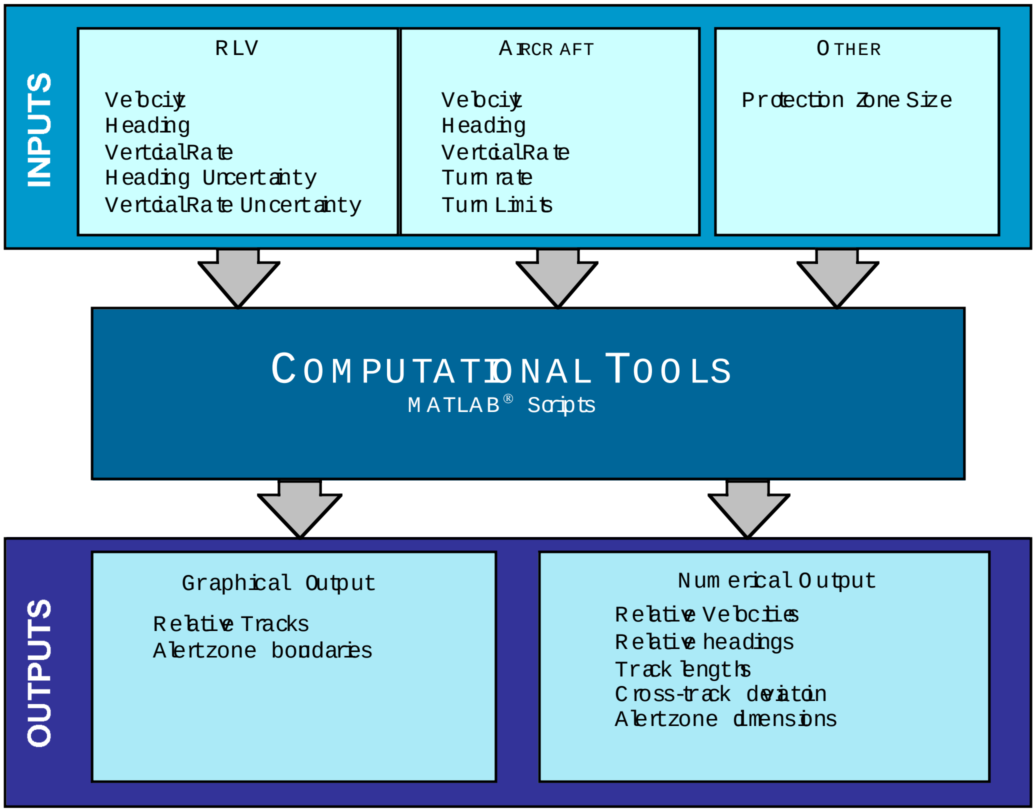

Figure 9: Tools suite schematic

The primary processing was done in MATLAB® through scripts. Subsequent data analysis was performed in MS Excel® Worksheets. Various combinations were used for the horizontal and vertical planes, and for varying degrees of uncertainty, utilizing structured multi-level routines in some cases. The RLV parameters needed are velocity, heading, vertical rate, and heading and vertical rate uncertainties. The input aircraft parameters are velocity, heading, vertical rate, turn rates, vertical accelerations, and altitude change and turn angle limits. The Protection Zone geometry to be used is also defined. The MATLAB® scripts provided graphical output of relative tracks, and simple and combined Alert Zones. Numerical output data used for further analysis includes relative velocities, relative headings, track lengths, cross-track deviations, Alert Zone dimensions, and temporal measures.

3.3 Parametric Effects

In this section we examine some effects of parametric variations on Alert Zone geometry.

The baseline Alert Zone is shown in Figure 10 for intruders approaching head on. No uncertainty in tracking or path prediction is assumed. Both the intruder and ownship are travelling at 450kt and a 20 second delay between a conflict alert and actual start of an avoidance maneuver is assumed. The avoidance maneuver is a 30° bank turn left or right, equivalent to a turn rate of 1.4°/s. The protection zone is a circle of 5 NM radius. We use the apex distance (27 NM in this example) as the measure of Alert Zone size. As shown, an intruder directly ahead of the ownship would produce a conflict alert aproximately 27 NM ahead, at which time the ownship would have to turn to avoid the conflict.

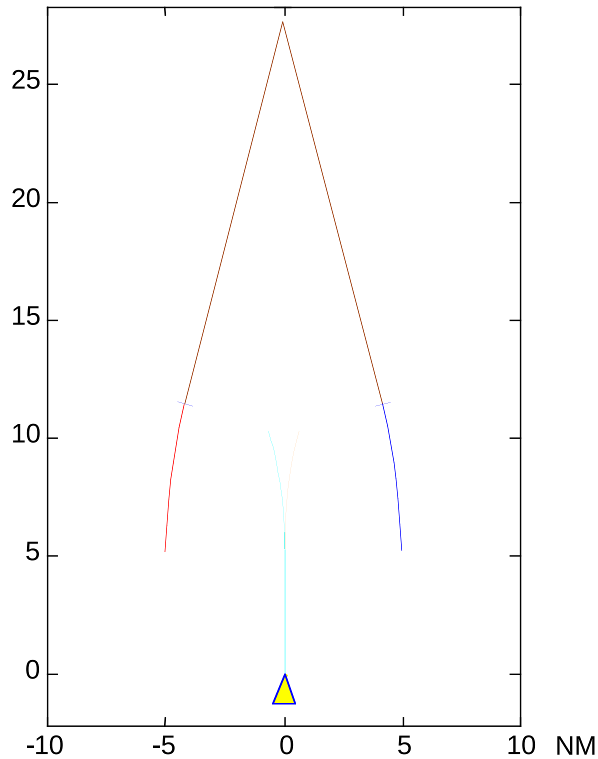

Figure 10: Baseline Alert Zone

Turn Angle:

As the size of the Alert Zone is inversely related to the severity of the avoidance maneuver, we can perform a trade-off between maneuver severity and the distance from the projected conflict at which the maneuver is initiated. Less severe maneuvers must be started earlier, and more severe ones can be delayed until later. Figure 11 shows the Alert Zones for turns of 15°, 30°, 45°, and, 60°, for a head on intruder. Increasing turn angle reduces the range at which the avoidance maneuver must be initiated, but causes a larger penalty per unit time, as the velocity component in the direction towards the destination is reduced.

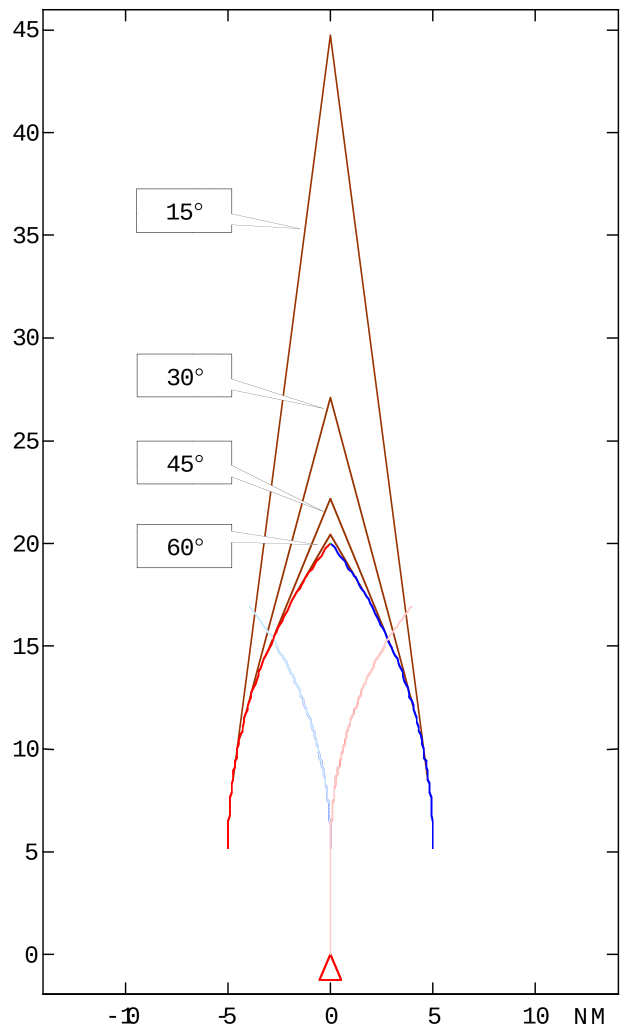

Figure 11: Effect of Maximum Turning Angle

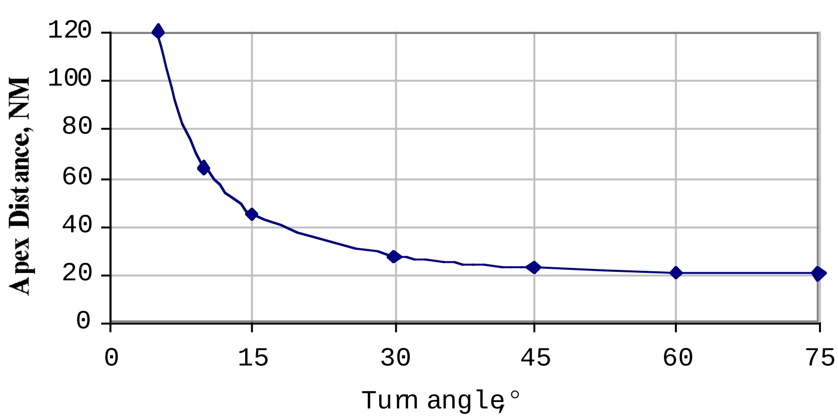

Figure 12: Apex Distance vs. Turn Angle

Figure 12 shows the variation in Apex distance with increasing turn angle. As shown, there is little benefit in increasing the turn angle beyond 30°.

Turn Rate:

We have thus far assumed a turn rate of 1.4°/s, which corresponds to a bank angle of 30°. Figure 13 shows the effect of changing turn rate, for 45° turns. As the turn rate increases, the Alert Zone shrinks, approaching asymptotically the instantaneous turn rate Alert Zone, which is also shown. Figure 14 relates the Apex distance with turn rate. There is little benefit beyond turning rates of about 1.4°/s, as the fraction of time spent in the turn becomes smaller.

In Figure 13 the arcs radiating from the straight ownship track line in the center show the duration that the ownship spends in completing the turn, before the straight segment at the new heading. Since the speed is constant, the time spent in performing the turn is inversely proportional to the turn rate, and this is seen in the decrease of arc lengths as the turn rate increases. However, the decrease in arc length is compensated by the increase in the straight portion of the avoidance maneuver. In a head on conflict, 5 NM of deviation from the nominal track is required to solve the conflict in the worst case. The edge of the Alert Zone needs to intersect the centerline, and as the flight path arc length reduces, the curved boundary converges to 5NM radius, and the straight section of the Alert Zone boundary becomes longer.

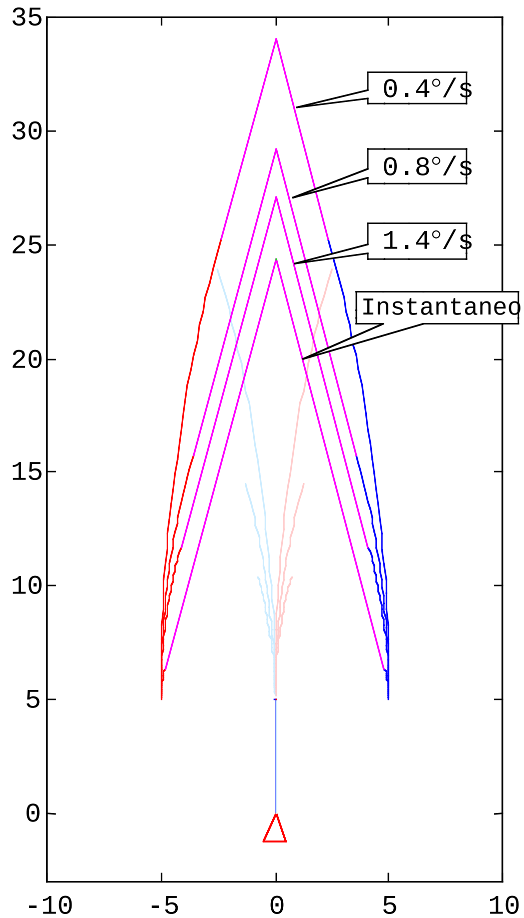

Figure 13: Effect of Turn Rate

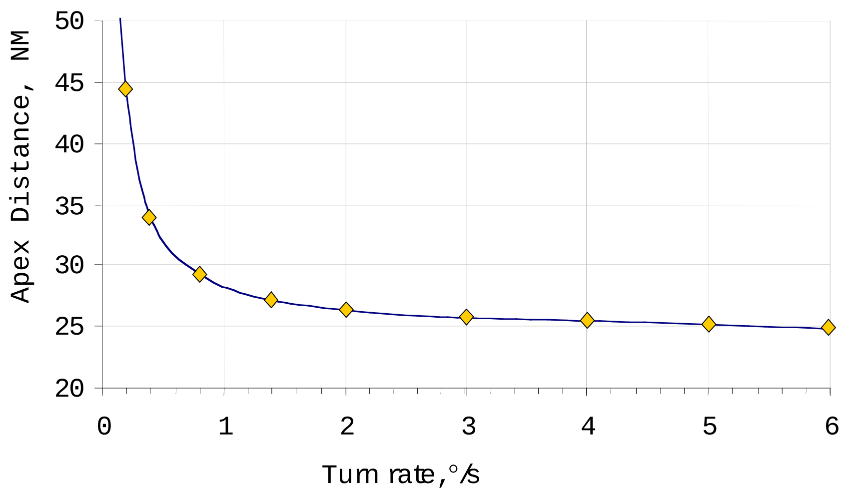

Figure 14: Apex Distance vs. Turn Rate

Intruder Speed:

The effects of intruder speed (V_I) for constant ownship speed (V_O) of 450 knots are shown in Figure 15. As the relative velocity increases, the Alert Zone is stretched linearly with it (Figure 16).

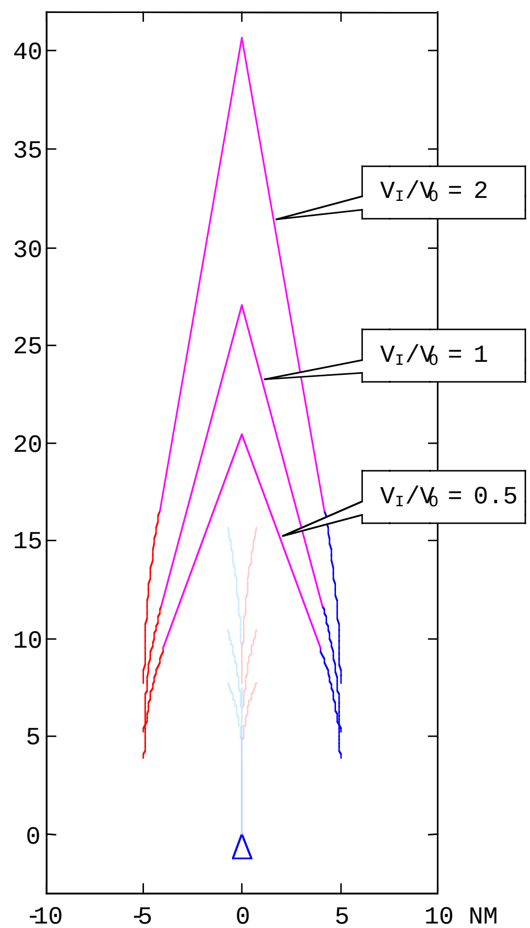

Figure 15: Effect of Intruder Speed
V_O= 450kt, V_I =225, 450, and 900kt

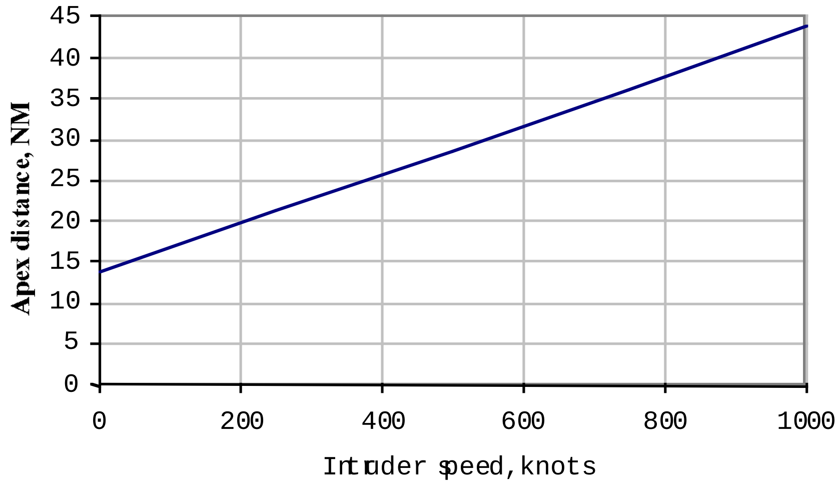

Figure 16: Apex Distance vs. Intruder speed

Relative Heading:

Figure 17 shows the Alert Zones for intruders at relative headings of 180°, 150°, 120°, 90°, 60°, 30°, and 1°. At 0° the intruder is static relative to the ownship and no conflict can occur unless the intruder is already inside the Protection Zone. The Alert Zones for the corresponding negative angles are simply mirror images of the zones shown here, due to symmetry.

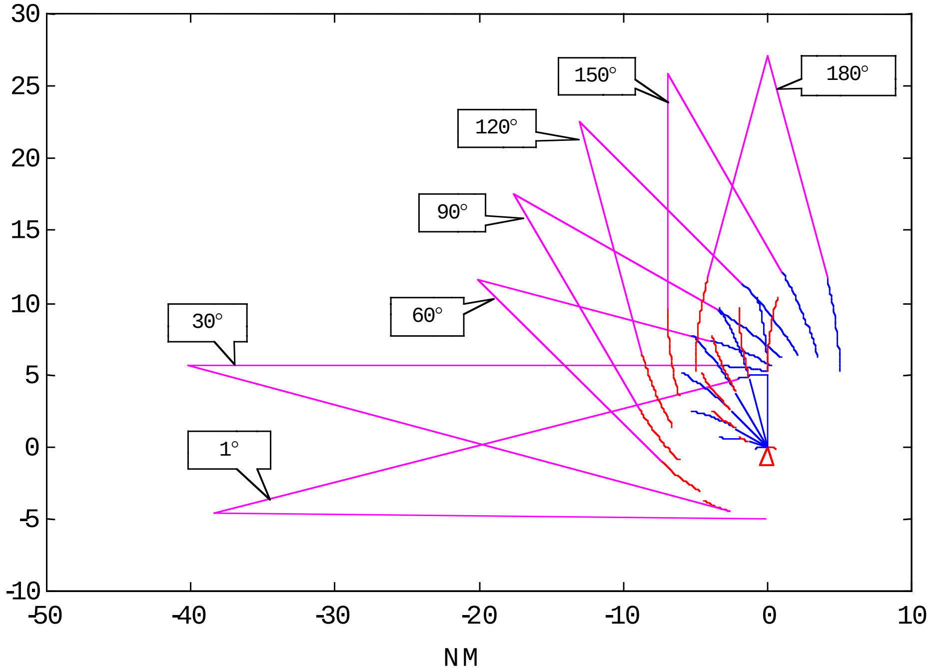

Figure 17: Effect of Relative Heading Angles (30° turn)

For relative heading angles larger than the turn angle (30° in this case), the Alert Zone does not substantially change its shape and points in the direction of the relative velocity.

The Alert Zones shown for 30° and 1° relative headings are larger than the others because they use a left turn or straight maneuver combination. If the turn angle is equal to the heading difference, turning right eliminates relative velocity ($\boldsymbol{v}_{rr} = 0$) as shown in the vector diagram in Figure 18. The ownship right turn vector and the intruder's velocity vector become identical. The Protection Zone then stops sweeping and becomes a static circle. We have the option of selecting the smallest shared area which is the shaded circle in the figure representing the static PZ, or the Alert Zone generated by changing the maneuver options from left turn or right turn to left turn or straight. Selecting the static circle means that the conflict becomes frozen in time, and does not get resolved. Switching to a left turn or straight combination we get a jump in alert zone size but we have the assurance that the conflict will be resolved in time, as there is significant relative velocity present. The elimination of relative velocity can only happen if both vehicles travel at the same speed.

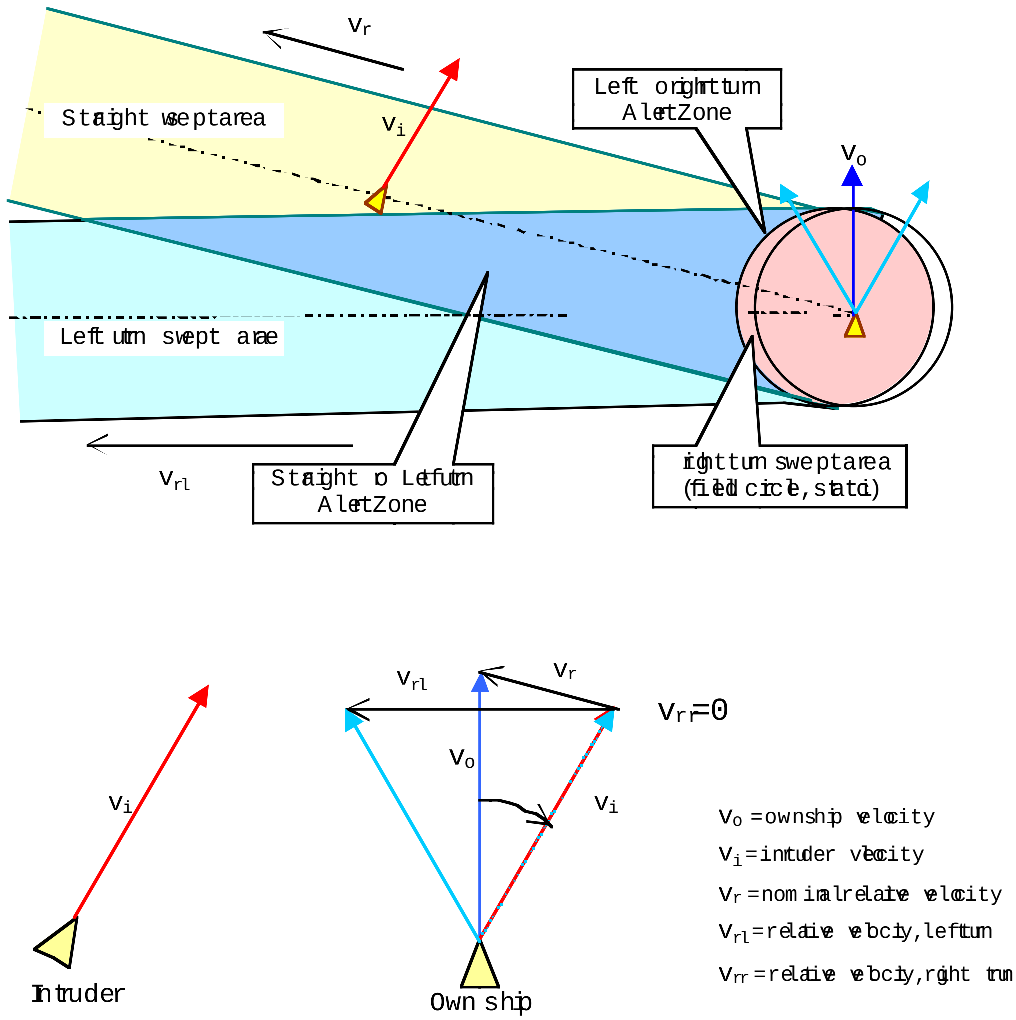

Figure 18: Alert Zones where turn angle is equal to heading dif-

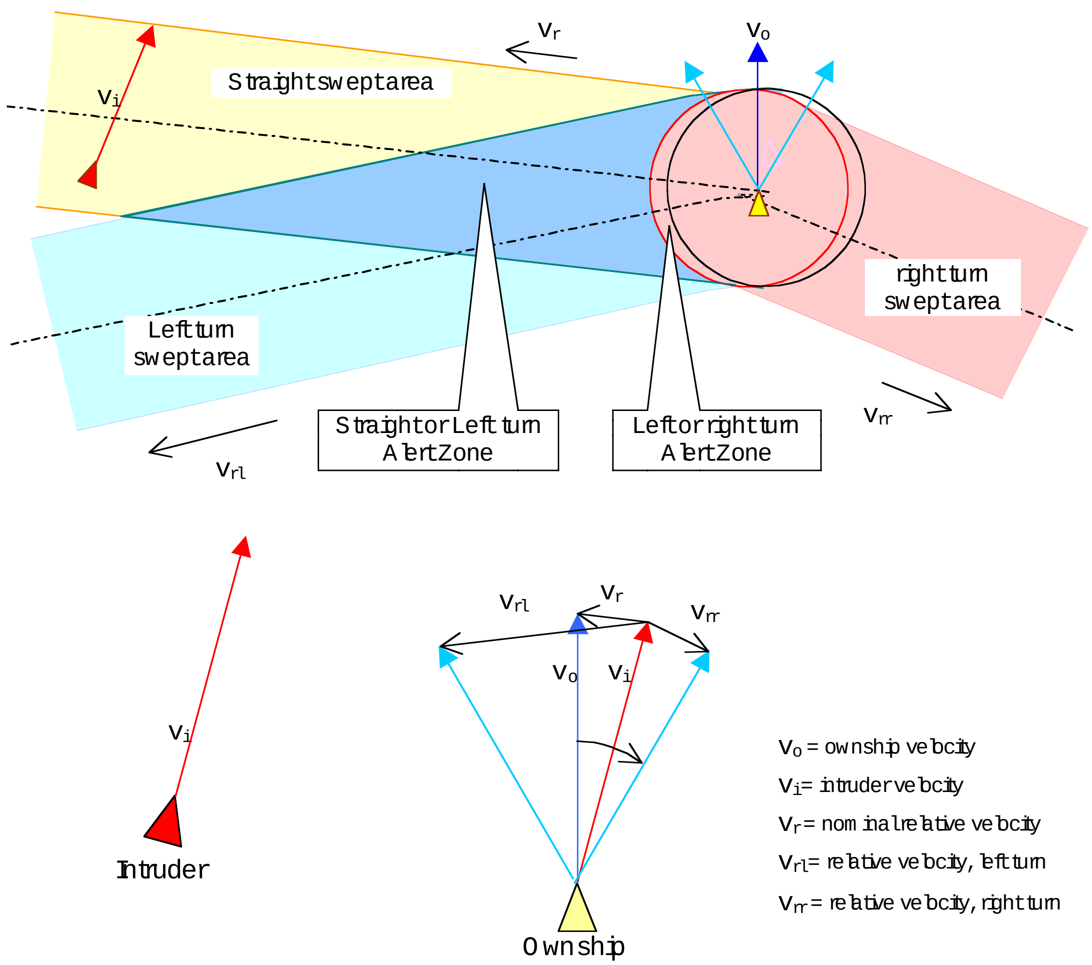

Figure 19: Alert Zones where turn angle is greater than heading d

A turn greater than the heading difference changes the relative velocity so that the intruder and ownship move away from each other as shown in Figure 19. The swept volume then also reverses course. The Alert Zone formed by combining the left turn and right turn swept volumes has approximately the shape of the Protection Zone itself, displaced slightly in the direction of the nominal relative velocity. Although the immediate conflict is resolved, we have to determine when to return to the original course. If we use this boundary option then we have to continue on the new heading until the intruder passes ahead before resuming the original heading. We also have the option of switching to the left turn or straight Alert Zone which is similar to that discussed before. This option solves the conflict in a more direct manner as before and is easier to use because a single turn rather than a combination of turns can be used to solve the conflict.

Thus, we decide that when the relative heading of the intruder is less than the turn angle limit, we should switch the maneuver alternatives from left turn or right turn, to left turn or straight. This results in a jump in Alert Zone size as shown in Figure 20. This indicates that for small heading differences, turn maneuvers alone have difficulty resolving conflicts unless large magnitude turns are performed.

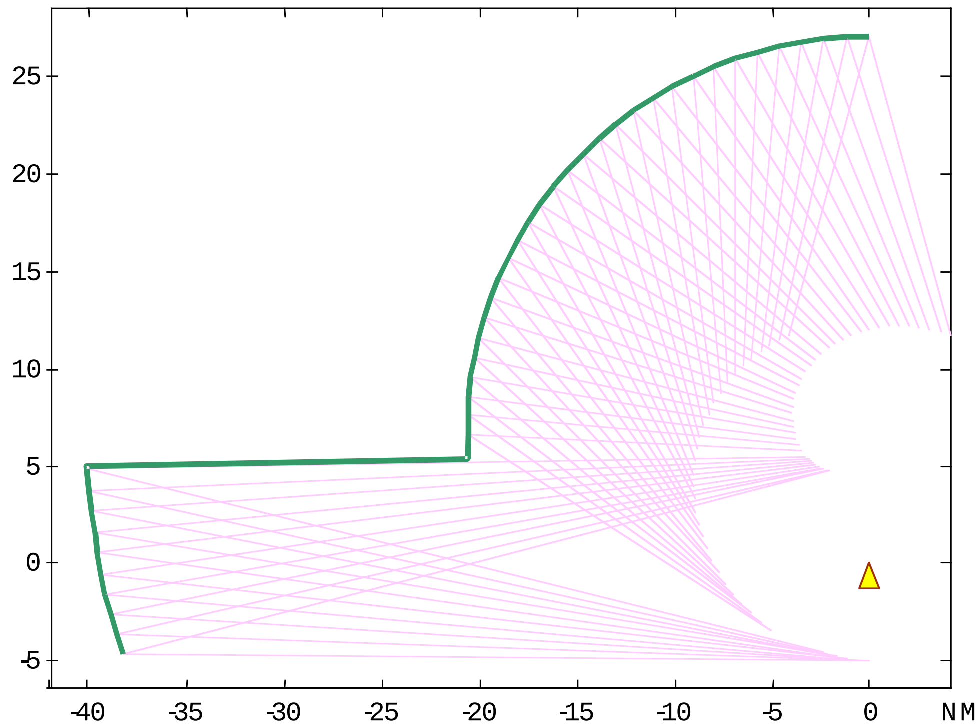

Figure 20: Envelope of Alert Zones for different relative heac
(intruder at same speed as ownship)

The complete envelope of the Alert Zones for different relative headings is shown in Figure 20. An intruder that approaches this envelope heading towards the ownship will require avoidance maneuvering. At the envelope crossing we determine the intruder's direction and use the appropriate alert zone to resolve the conflict.

For intruder speeds faster than the ownship, some turn angles may not resolve the conflict or do so inefficiently depending upon the nominal heading difference. The avoidance maneuver set being used is then reconsidered. As shown in Figure 21, A and B are two relative heading angles where a given heading change (right and left respectively), produces no change in angle of the relative velocity. For another heading difference C, an identical change in relative velocity angle is produced for both left and right turns, and the swept areas become parallel. The alert zone then becomes infinitely long.

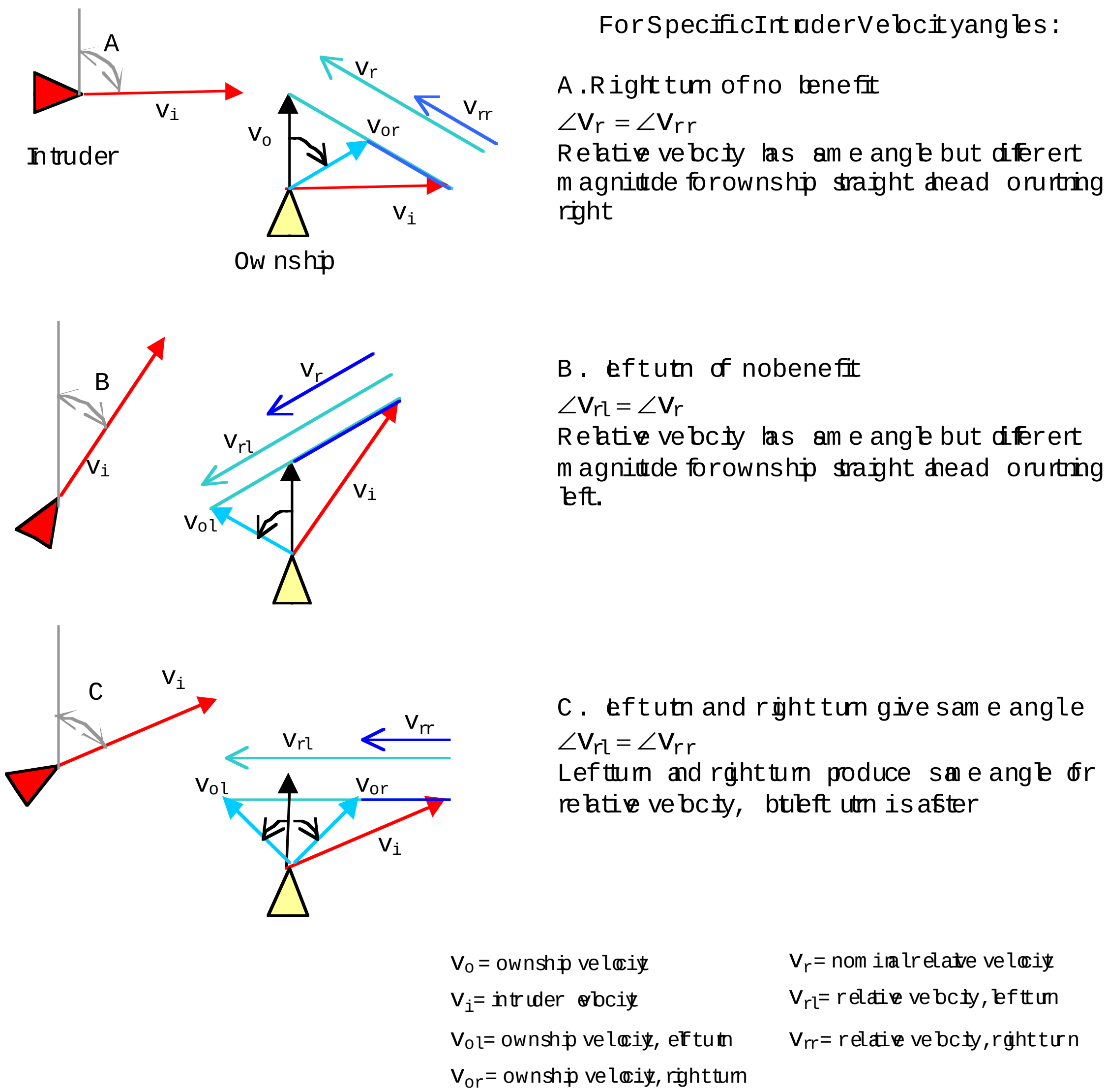

Figure 21: Relative headings where two different ownship velocit
same relative velocity angle

For heading differences between 180° and angle A, we use the left turn or right turn maneuver combination as the angle change of relative velocity for a left turn is in the opposite direction as that for a right turn, resulting in a finite Alert Zone. Between angle A and C, we switch to left turn or straight, as both left and right turns give an angle change of relative velocity in the same direction, but turning left resolves a conflict more quickly than a right turn. At C, the relative velocity angle changes from left and right turns are in the same direction and equal. Between angle C and angle B, the right turn gives a greater change than left turn, so we switch to right turn or straight. Between B and 0°, taking a left turn becomes useful again, as again the relative velocity angle change for a left turn is in the opposite direction as that for a right turn. Figure 22 shows an illustrative example. The nominal heading difference is between C and B. Hence the right-turn or straight combination gives us the smallest alert zone. A portion of the right turn or left turn alert zone is outside the straight swept area. Choosing that combination will cause some invalid alerts, and we would be asked to maneuver to avoid intruders that are not in nominally in conflict with the ownship.

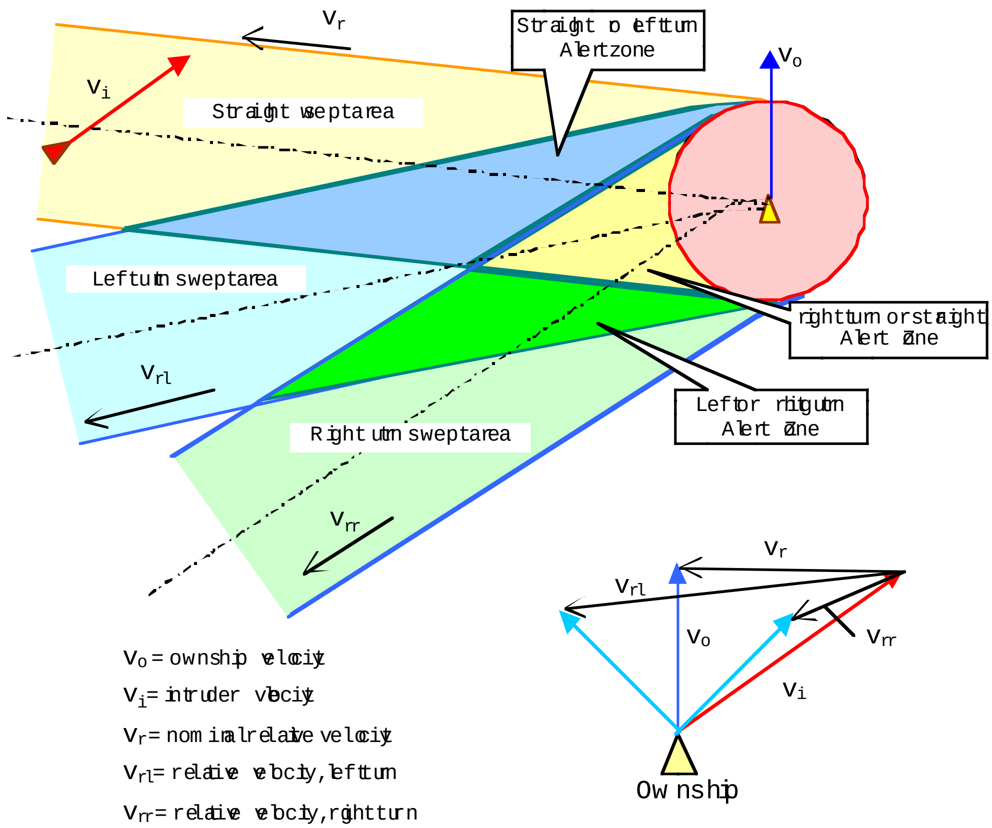

Figure 22: Alert Zones for heading difference between angles C

The Alert Zones resulting from these optimized maneuver combinations are shown in Figure 23, for an intruder flying twice as fast as the ownship. The points on Alert Zones where the combinations change are labeled. With larger turn angles it is possible to reduce the sizes of the Alert Zones significantly. Going to 45° turn angle, the 140NM breadth of the envelope in Figure 23, can be reduced to 72NM, while the other dimensions are reduced by smaller factors. However, there might be unfavorable changes in the maneuver penalty due to increased turning angle even though we need to employ it for a shorter time, so the selection of turn angles should be done with care.

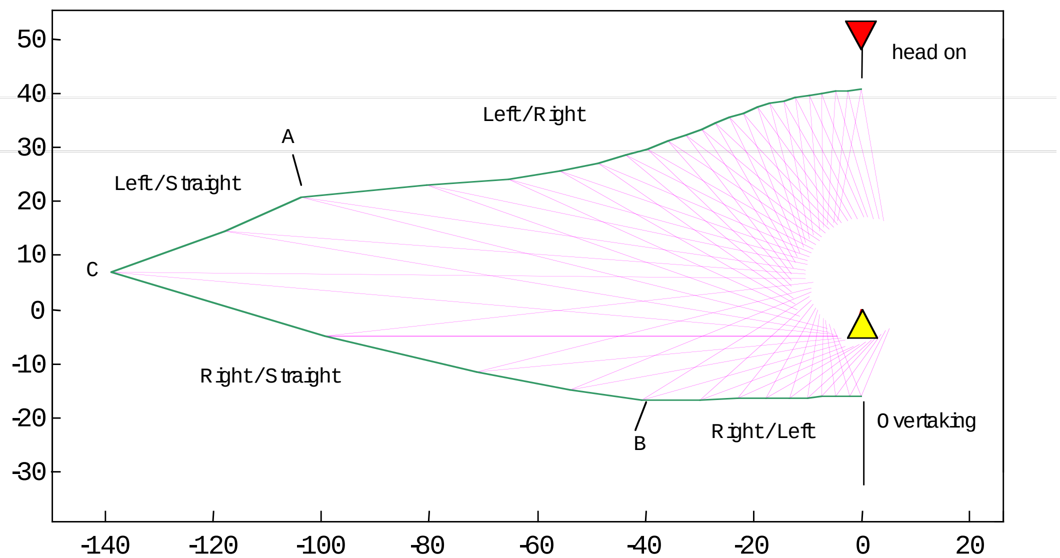

Figure 23: Maneuver combinations for different relative headin
($V_I / V_O = 2$)

For intruder velocities less than the ownship, these difficulties do not exist as the relative velocity angles are confined to the forward half-plane, and the left turn or right turn combination always works efficiently.

3.4 Uncertainty

The Protection Zone (PZ) used is 5NM radius by 1000ft or 2000ft altitude difference. We can allow for position uncertainty, for example due to sensor limitations, by increasing the size of the Protection Zone used in determining the Alert Zones by the position uncertainty (Figure 24). The safety buffer is then increased and we are assured that PZ penetration will not occur.

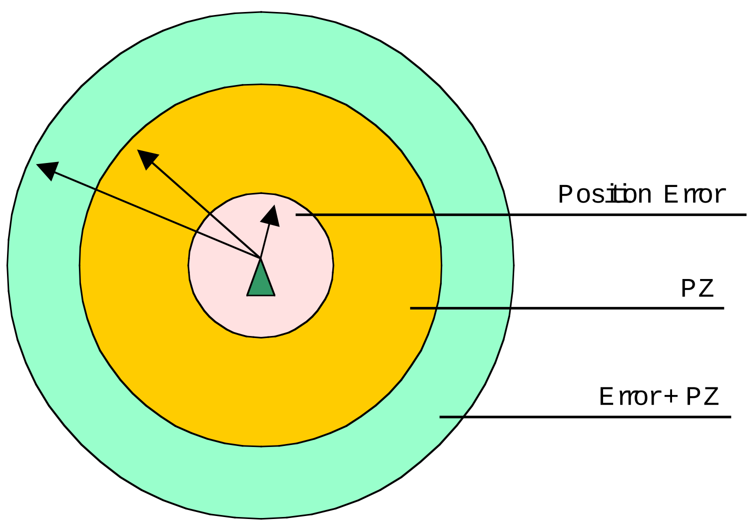

Figure 24: Combined Error and Protected Zone

We can also formulate Alert Zones for encounters where speed or heading uncertainties may exist. These uncertainties may be due to sensor error or may represent a desired safety buffer that grows with time to protect against catastrophic failure. If such an uncertainty can be bounded, then we can find an Alert Zone that resolves all conflicts within the maneuvering capabilities of the ownship. Figure 25 shows a horizontal-resolution Alert Zone for a head on encounter where both the intruder and the ownship are traveling at 450knots. The Alert Zones for zero heading uncertainty and for ±10° heading uncertainty are shown superimposed. The scales are in nautical miles and the ownship is allowed to turn 30° left or right. To develop this Alert Zone we determine the Alert Zones for 170° and 190° relative heading angles, which are the limits of uncertainty. We then project the outer edges of these Zones until they meet. An intruder inside this larger Zone but still outside the smaller ones can be avoided if it has no heading uncertainty. However, if the uncertainty is present for an intruder such as B inside this area, we might select a left turn based upon the 170° left turn swept area. If B turns out to have a heading of 190° then avoidance will fail, as the position B is intersected by the 190° left turn. Enlarging the Alert Zone in the manner shown avoids this danger and successful avoidance is assured. This procedure is discussed in detail in the Appendix.

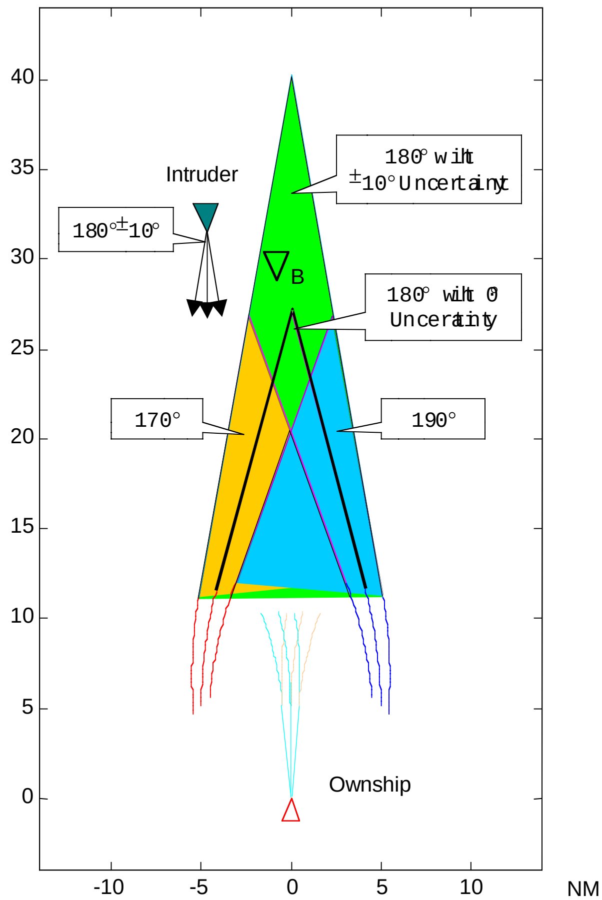

Figure 25: 180° ±10° Alert Zone compared with 180° ±0° Alert Zone
(30° turns)

Adding relative heading uncertainty increases the Alert Zone size as shown in Figure 26. The maximum lateral deviation from the original track also increases with uncertainty (Figure 27), as can be noted from the increase in length of the straight edges of the Alert Zone. The Alert Zone boundary arcs stay the same, as they are only dependent on the turn angle and turning rate.

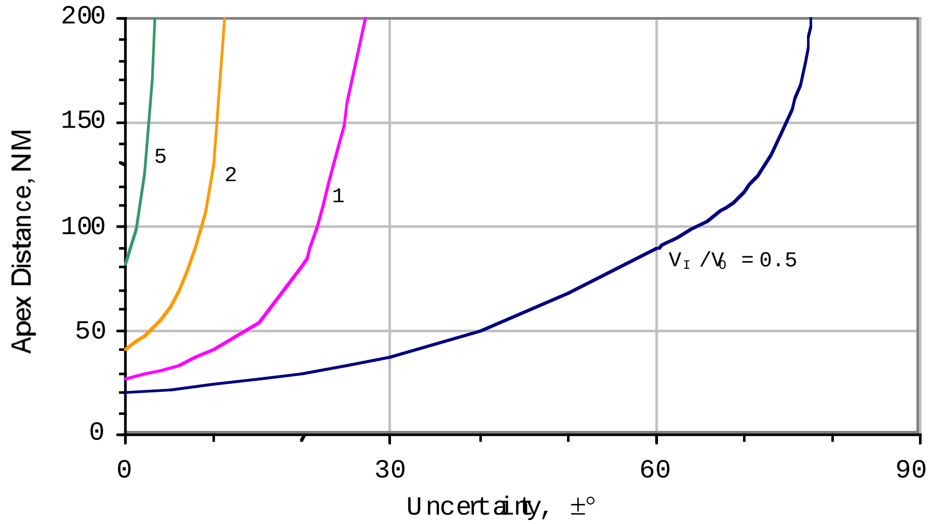

Figure 26: Apex distance vs. intruder heading uncertainty (30°

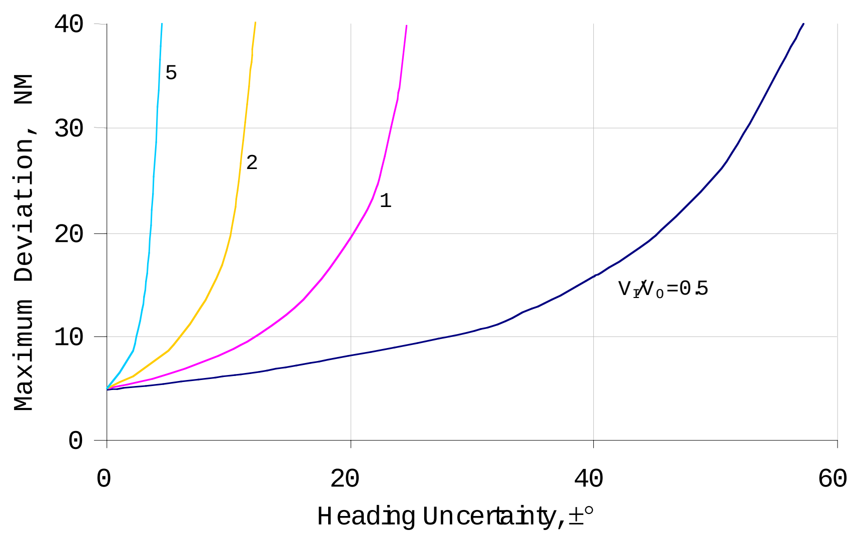

Figure 27: Maximum Deviation vs. Uncertainty (30° turns)

For intruder velocities greater than that of the ownship, there is an upper limit to the uncertainty angle, beyond which avoidance cannot be guaranteed no matter how much we are allowed to turn. For angle uncertainties larger than this limit, the Alert Zone becomes linearly divergent and its ultimate length and breadth become infinite. Should any intruder then appear within this divergent area, avoidance cannot be guaranteed (using turns alone). For intruder velocities less than the ownship velocity, it is always possible to find avoidance maneuvers that guarantee avoidance, although the Alert Zone size and avoidance cost rise with increasing uncertainty.

3.5 Alert Zones in the Vertical Plane

Vertical avoidance is accomplished by changing the vertical speed of the aircraft and differs from horizontal avoidance by a number of factors. The horizontal cross-section of the Protection Zone is circular (5NM radius) and allows simpler analysis since it retains a single dimension when viewed from all aspects within the plane. The vertical cross-section is a narrow rectangle (5NM x 1000ft), and does not offer the same simplicity. The long side of this rectangular zone is perpendicular to the vertical speed change direction, and as the relative velocity becomes closer to vertical, the longer aspect of the rectangle comes to bear, increasing the size of the Alert Zone. Additionally, there are no limits to the turn angle in the horizontal plane, whereas in the vertical plane there are limits to allowable vertical speed and the allowable altitude change. These limits vary according to the performance characteristics of the aircraft and phase of flight. The maximum vertical rate is generally small compared to the forward velocity and can be achieved by relatively small vertical acceleration for a short period. Consequently, increasing the vertical accelerations does not have a large impact on the Alert Zone size and maneuver penalties. It is therefore reasonable to neglect the time spent in the vertical acceleration phase and instead include this time in the assumed time delay.

The same procedure as used above can be followed to determine the Alert Zone in the vertical plane. The vertical cross-section of the cylindrical Protection Zone is rectangular (10NM wide by 2000ft high). The maneuver limits analogous to the left and right turn angles used previously are the maximum climb and descent rates. Figure 28 shows the Alert Zone for an intruder coming head-on with zero vertical speed. The maximum altitude change required for avoidance is ±1000ft if the intruder is at the same altitude (at the apex). The vehicles are travelling at 450kt and the ownship is allowed ±2000ft/min vertical speed, and has a 1.25g maximum load factor. The initial delay is 20 seconds. In this example, the apex of the alert zone extends 18 NM from the ownship

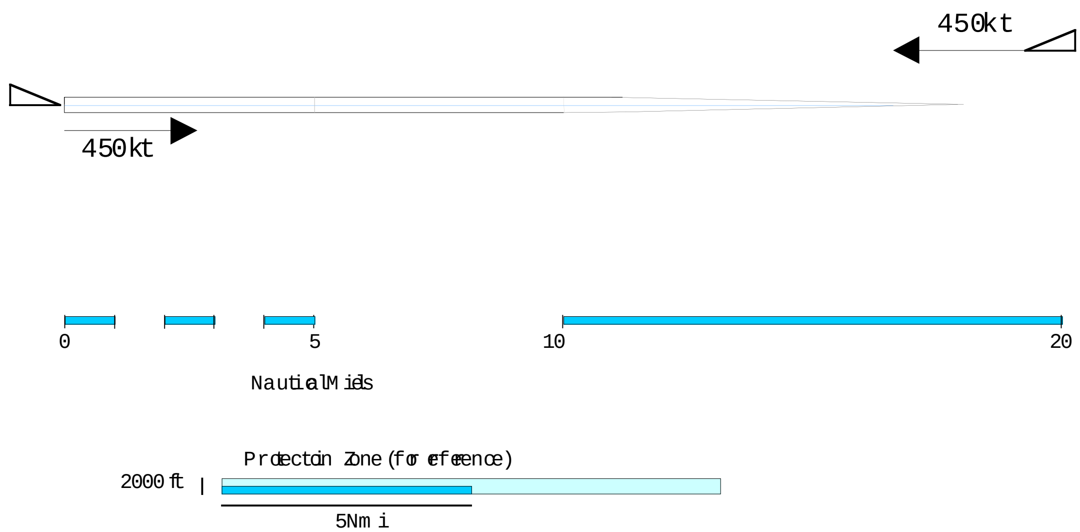

Figure 28: Vertical Alert Zone for an intruder with zero vertica

If the intruder has a high descent rate, the Alert Zone becomes much larger. Figure 29 shows the Alert Zone for 10,000ft/min intruder descent rate, with the 0ft/min Zone at the same scale for comparison.

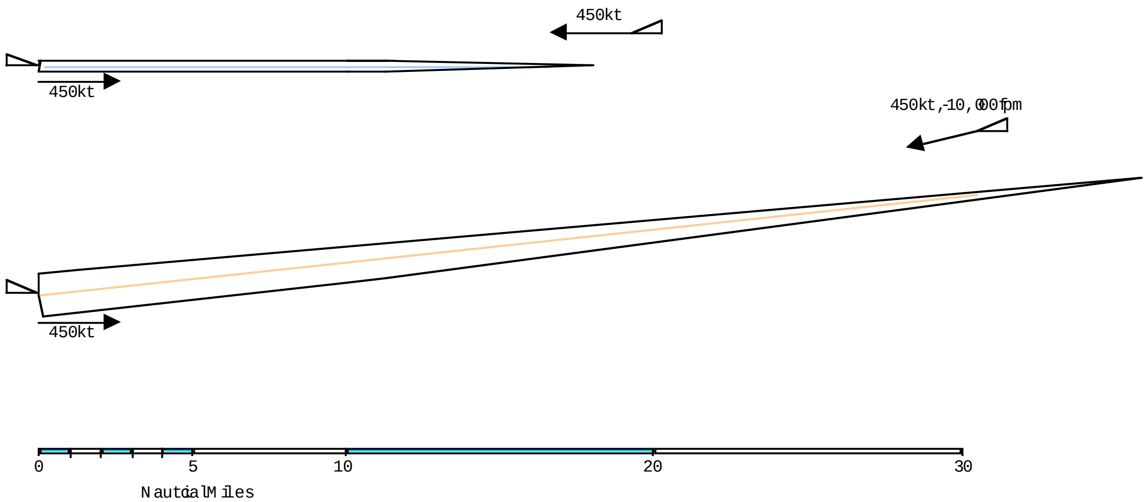

Figure 29: Alert Zone comparison, 10,000ft/min and 0ft/min intr

There are two distinct regimes for vertical avoidance. If the intruder vertical rate is within the limits of the ownship, then the ownship passes by the ends of the nearer, smaller side of the Protection Zone rectangle. If the intruder vertical speed is larger than the ownship's maneuvering limits, the ownship has to pass by the diagonally opposite corners of the Protection Zone rectangle, and the Alert Zone becomes significantly larger. At the point where the intruder vertical rate becomes larger than the ownship vertical rate limits, a jump in the Alert Zone size and the required maneuver size (total altitude change) occurs. Increasing ownship vertical rate reduces the range at which the avoidance maneuver must be initiated, and pushes the intruder vertical rate crossover-point out further.

Adding vertical rate uncertainty increases the Alert Zone size and the required maximum deviation from original altitude in a similar manner to the horizontal plane case. The range of effective vertical rates for the ownship is equal to the upper limit of the intruder vertical rate uncertainty. For vertical rates uncertainties larger than this, the Alert Zone becomes linearly divergent and its length and breadth go to infinity.

4 Alert Zone Comparisons

It is clear from the previous chapter that vertical maneuvers can be more effective than horizontal maneuvers in some cases but less so in others. We need to determine methods to compare both simultaneously.

4.1 Vertical Avoidance Kinematics

The geometry of vertical avoidance is a bit more involved than horizontal avoidance. We start with the intruder on a nominal collision course with the ownship, meaning that it lies on the projected relative velocity vector from the ownship position.

Figure 30 shows two head on cases, one with both the intruder and the ownship level and the other with the intruder having a large vertical rate. The nominal path leads to direct collision in each case. To avoid the intruder, the ownship needs to get enough vertical displacement that it misses the Protection Zone (PZ). We define the contact point as the point at which the ownship comes closest to the PZ boundary of the intruder. This contrasts with the Point of Closest Approach (PCA), which can be used in horizontal avoidance, but not vertical avoidance, as the horizontal PZ is circular while the vertical PZ is rectangular. For avoidance, we move the point of contact with the PZ to the edge of the protection zone, so that the relative trajectory just misses the protection zone and separation is maintained. This is achieved by climbing to 1000ft above the intruder altitude at this point, as the ownship passes into the horizontal projection of the intruder's protection zone.

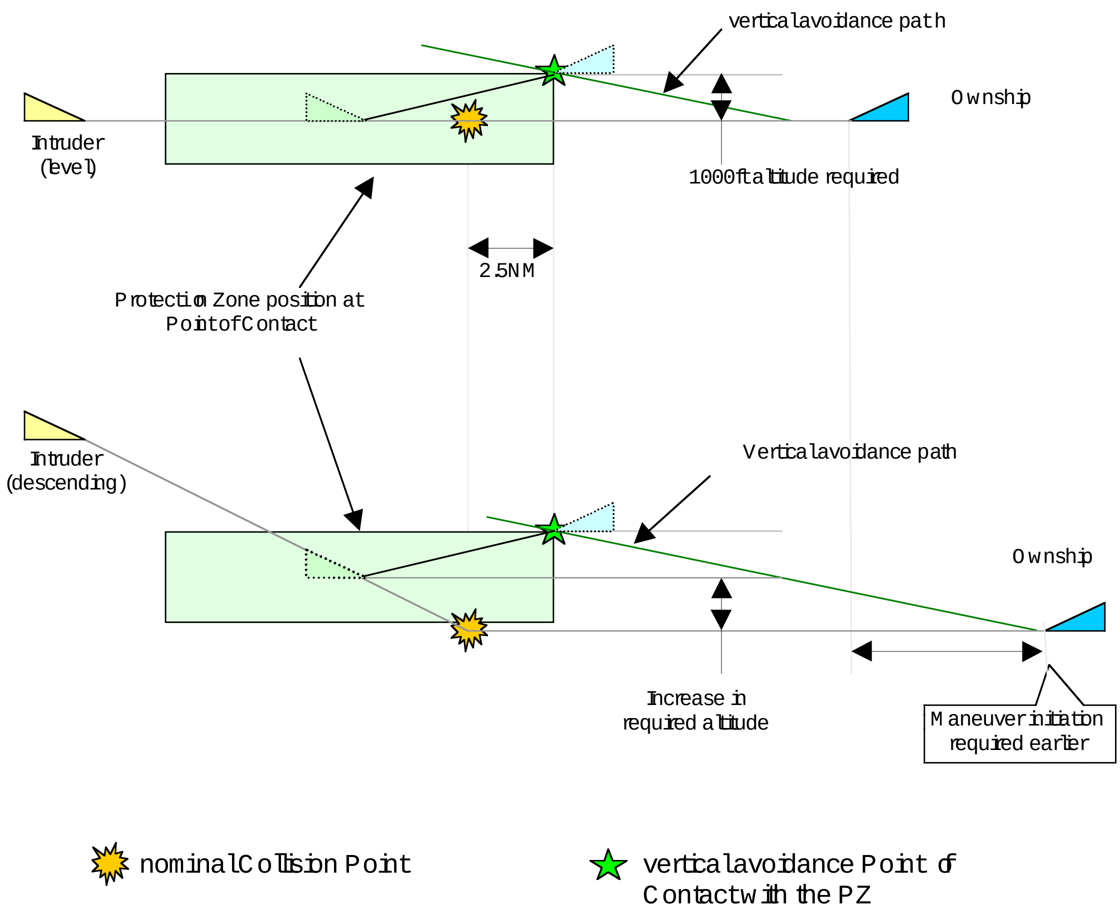

Figure 30: Vertical avoidance point of contact with the PZ for l
conflicts

As can be seen in Figure 30, with both the intruder and the ownship at equal horizontal speed, the contact point needs to be 2.5NM (5NM / 2) behind the Collision Point. The positions of the intruder, its PZ, and the ownship are also shown at the instant that the ownship reaches the Contact Point. If the intruder is level, then we only need 1000ft to clear the PZ. For other descent rates, we have to account for the height change that the intruder undergoes between the Contact Point and the Collision Point, and then add 1000ft to get the required climb. As the altitude required increases, the point at which the maneuver must be initiated has to be moved back. Thus, we are able to determine the required altitude that needs to be climbed for avoidance, and the distance that the maneuver must be initiated before the projected collision time.

The analysis is similar for avoidance using descent rather than climb. However, if the descent rate of the intruder is greater than what the ownship can manage, then the point of contact is moved to the far side of the protection zone, and a jump in the required descent is needed.

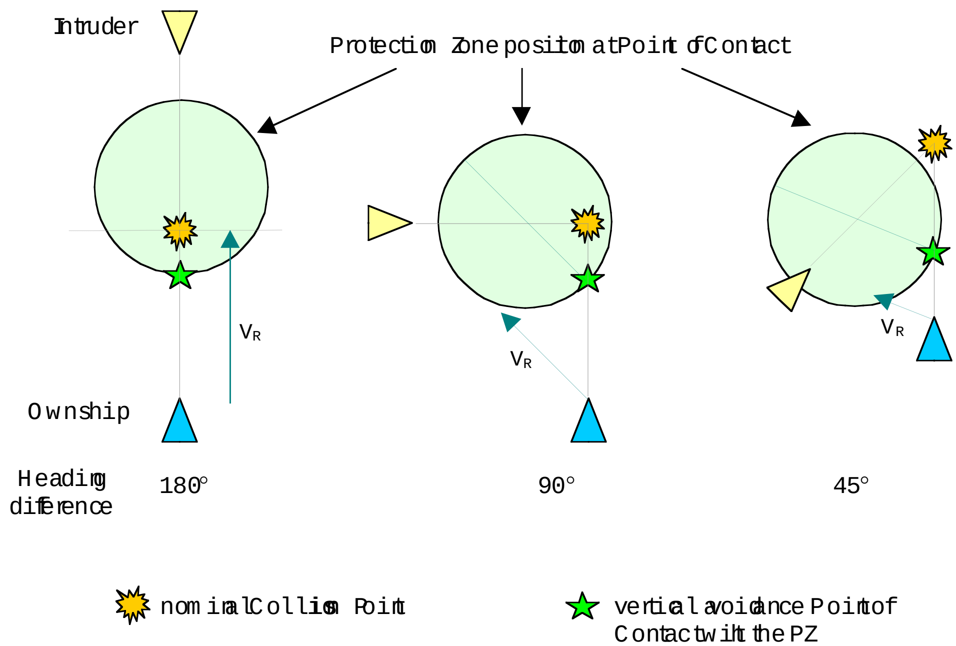

Figure 31: Vertical avoidance point of contact with the PZ for c
relative headings

If the heading difference is smaller than 180° then the point of contact needs to be moved further than in the head-on case, as shown in the Figure 31 for 180°, 90° and 45° heading differences. Due to reduction of the angle between the flight tracks, the required point of contact moves further away from the point of collision. The moving of the point of contact further increases the required altitude change due to the intruder’s vertical rate. The ownship approaches the intruder at a steeper angle as the relative horizontal speed is reduced while the relative vertical speed does not change.

The variation in required climb with heading difference is shown in Figure 32 for intruders with the same horizontal speed as the ownship, and in Figure 33 for those twice as fast. The increase in required climb with decreasing heading differences is clear for RLV descent rates different from zero. For zero vertical speed, the climb required is 1000ft for all relative headings. However, if the relative velocity is vertical and we are limited to changing the ownship velocity vertically, conflict resolution becomes impossible. For equal horizontal speed, as the heading difference becomes smaller this condition is approached, and asymptotically large altitude changes are required near zero heading difference. For an intruder with horizontal speed different from the ownship such as in Figure 33, the relative velocity cannot become vertical and the asymptotic behavior is absent. However, as can be seen from the figure the altitude changes required can be large enough to be impractical.

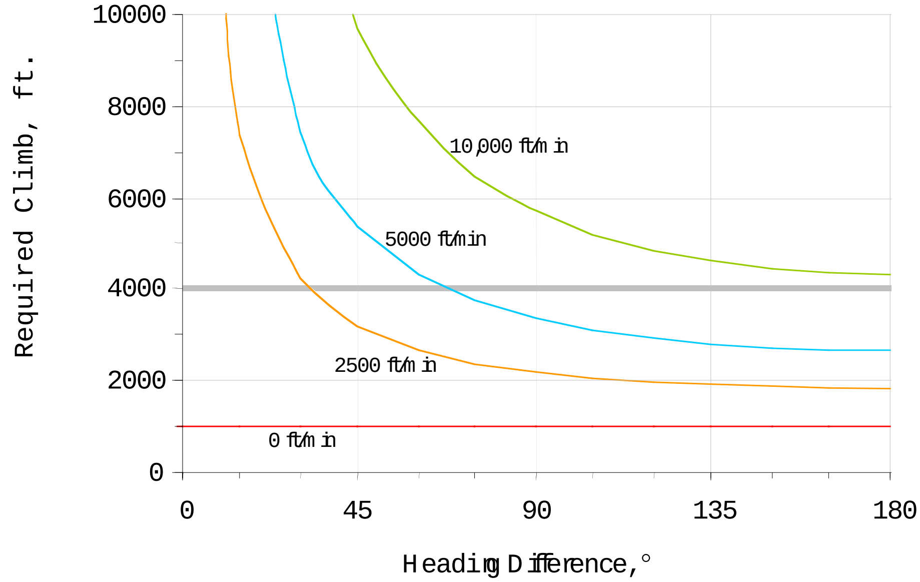

Figure 32: Required altitude change for vertical avoidance with a
of equal speed, zero miss distance conflict

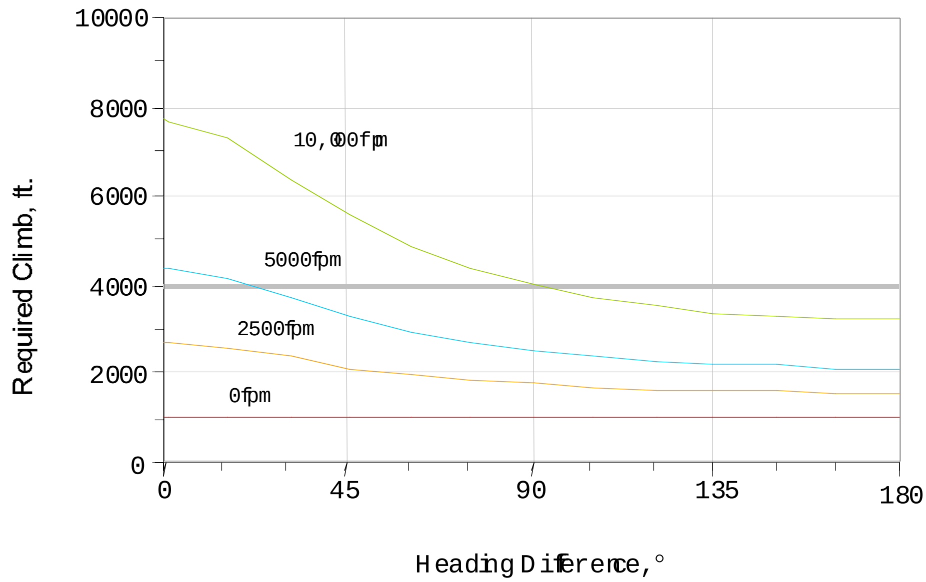

Figure 33: Required altitude change for vertical avoidance, $V_I/V_O = 2$

4.2 Vertical Avoidance Alert Zones in the Horizontal Plane

We can determine the horizontal projections of the vertical avoidance Alert Zones for intruders. These projections show the variations in horizontal distance at the time at which the maneuvers must be initiated, and allow comparison with Alert Zones for horizontal avoidance. The analysis in this section is slightly different from that used earlier in that we assume a direct collision course and then determine the distance before the projected collision at which a given vertical maneuver must be initiated.

Figure 34 shows the horizontal projection envelopes of the vertical avoidance Alert Zones for intruders descending at 10,000, 5000, and 0 ft/min through the ownship's altitude on a nominal collision course. When such an intruder crosses the envelope, the ownship is expected to climb to avoid the intruder. As mentioned before, if descent is used for avoidance rather than climb, the Alert Zones can also be similarly found with allowances for the changes in the encounter geometry. The boundaries in Figure 34 represent the horizontal distance that an intruder with a certain descent rate may be allowed to approach, before the vertical avoidance maneuver has to be initiated to guarantee avoidance. In Figure 34, intruder A is approaching head on and has a larger relative velocity than intruder B, which is approaching with a smaller heading difference. The relative speed of the intruders depends on their heading angles and is the vector difference between the ownship and intruder velocities.

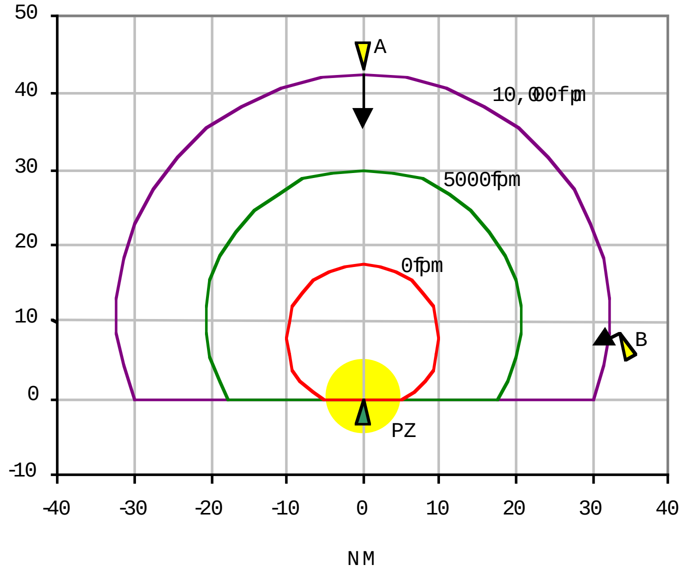

Figure 34: Alert Zones for vertical avoidance for an intruder on collision course, $V_I/V_O = 1$

The alert zones for an intruder with horizontal speed twice that of the ownship are shown in Figure 35. The required altitude changes for different heading differences were shown in Figure 33.

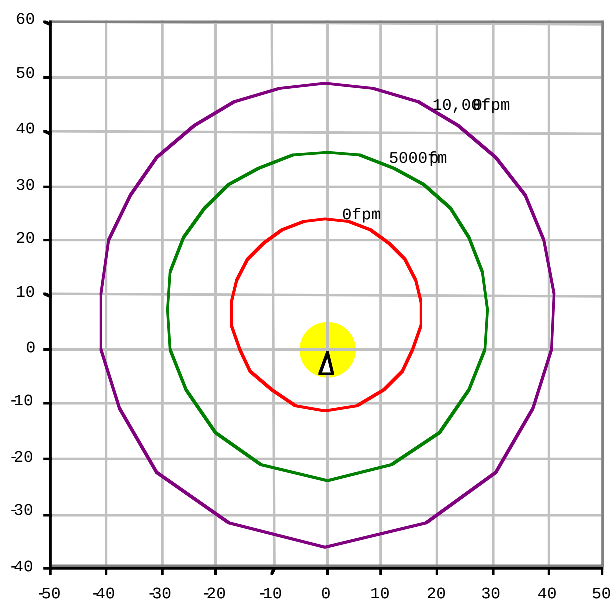

Figure 35: Alert Zones for vertical avoidance, $V_I/V_O = 2$

Most RLVs will not have the option of holding constant altitude. With RLV vertical rates beyond those of conventional aircraft limits (e.g. 4000ft/min), the altitude change required to resolve these conflicts becomes large enough that vertical avoidance will cease to be an option. For example, if we limit altiude changes to 4000ft. we can see from Figure 32 that it will not be possible to ensure vertical resolution of a conflict with an RLV descending at 10,000ft/min, using only climb. It will be possible to vertically resolve conflicts with an RLV descending at 5000ft/min with climbs smaller than 4000ft but only for heading differences greater than about 70°.

4.3 Comparing Horizontal and Vertical Alert Zones

The alert zones for vertical and horizontal avoidance are shown on common axes in Figure 36. The vertical alert zones are the same as those in Figure 34, while the shaded horizontal avoidance alert zone uses a 30° maximum turn angle as in Figure 20. The horizontal alert zone is not affected by the vertical speed of the RLV. Referring to Figure 32, assuming a climb limit of 4000ft, an intruder descending at 10,000ft/min cannot be avoided at all, while one descending at 5000ft/min can be avoided if its heading difference is greater than 70° (as mentioned above). This heading difference range is shown by the thickened arc in Figure 34. Thus, for 5000ft/min and heading differences of greater than about 70° vertical maneuvering is possible, while horizontal turns only are feasible for heading differences less than 70°.

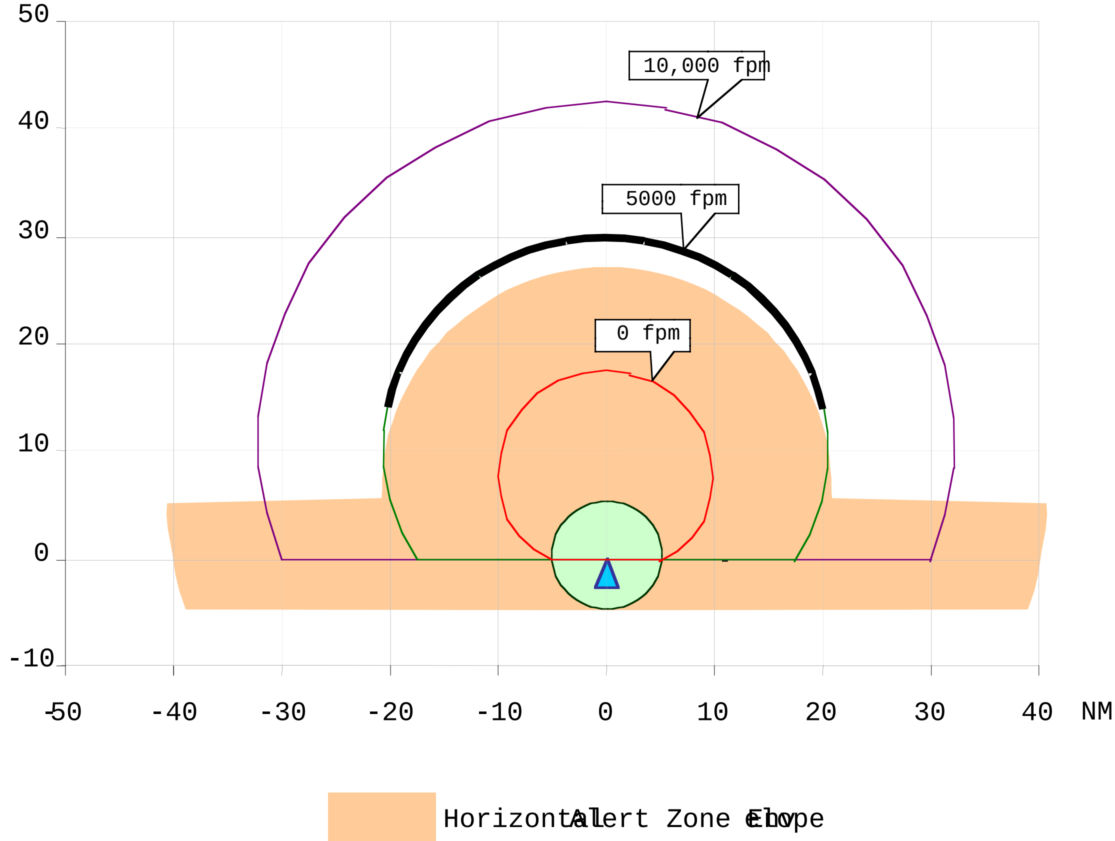

Figure 36: Comparison between horizontal and vertical avoidance alert zones in the horizontal plane

4.4 Tradeoffs Comparing SUA and Tactical Avoidance Modes

We can determine the costs associated with following the avoidance strategy by employing the attributes of the alert zone developed in the last chapter. The alert zone gives us basic information on sensing requirements in terms of time and distance. Its geometry allows us to determine the necessary deviations from the nominal flight path and the increments in distance that are incurred when following the avoidance paths and their distributions. With this information, we can optimize the maneuvers to minimize the penalties or the duration that the vehicles are in potentially hazardous proximity.

The objective is to make meaningful comparisons between separation control options to determine the most efficient strategy. A number of criteria exist to compare the options based on effective penalties or costs for equivalent safety levels. Penalties for a maneuver can be defined in terms of additional time, additional distance, or deviation from the original track that the avoidance maneuver causes. Each of these can be converted to costs (e.g. increase in direct operating cost), by appropriate conversion functions. Additional effects such as differences in workload and equipage requirements also need to be examined

All aircraft traversing an SUA have to divert when it is active, whereas tactical avoidance requires only those with expected conflicts to take avoidance maneuvers. To determine the costs for avoidance, the number of aircraft affected needs to be determined along with the cost to each aircraft. For example, the diversions caused by the current SUA around KSC is estimated to add 8 to 10 minutes of flight time on average [6, 7].

Tactical avoidance can be visualized as actively detecting conflicts between traffic and the RLV, and determining whether and how avoidance needs to be performed. The avoidance maneuver is then selected according to the avoidance rules. The avoidance strategy used feeds into the costs to traffic flow, workload and other factors.

4.4.1Deviation from Nominal Path

We can evaluate how much the aircraft are displaced from their normal paths to make a comparison between the costs for SUA and tactical conflict resolution. For example, if the SUA were modeled as a cylinder 60 NM in diameter with unlimited height, then all aircraft with nominal paths intersecting with the SUA would need to divert laterally. The average lateral diversion would be 15NM if a uniform distribution were assumed, while the maximum lateral diversion required would be 30NM. Either of these measures can be used to compare with a tactical conflict resolution strategy. To compare overall costs, the total number of aircraft diverted would be factored into the calculation.

For a head on conflict, the maximum tactical deviation is approximately 5NM as long as there is no uncertainty. As uncertainty in intruder heading increases, the maximum deviation increases, since we must protect against the entire range of intruder headings (Figure 25 and Figure 27). For head-on conflicts, uncertainty in speed does not affect the needed deviation from nominal path. For conflicts at other angles, the speed uncertainty is translated into an additional angular uncertainty when we subtract vectors to obtain the relative velocities. We can plot these for various speed ratios to determine the values of speeds and heading uncertainties for which SUA offers lower penalty than tactical avoidance.

As an example, assuming a maximum deviation of 30NM with an SUA, we use Figure 37 to determine for each speed ratio the allowable heading uncertainty. Plotting this data in Figure 38, we can see that as intruder uncertainty and speed are increased a point is reached at which SUA becomes more effective in resolving conflicts than the tactical approach. For example, at a speed ratio of 1, up to 24° of heading uncertainty can be managed tactically; beyond 24° SUA incurs a smaller lateral deviation on aircraft.

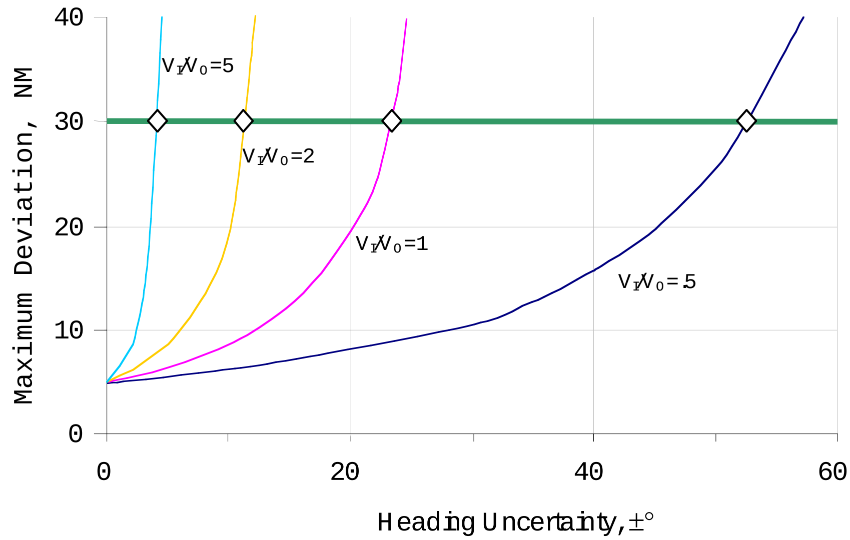

Figure 37: Maximum Deviation vs. Uncertainty (c.f. Figure 27)

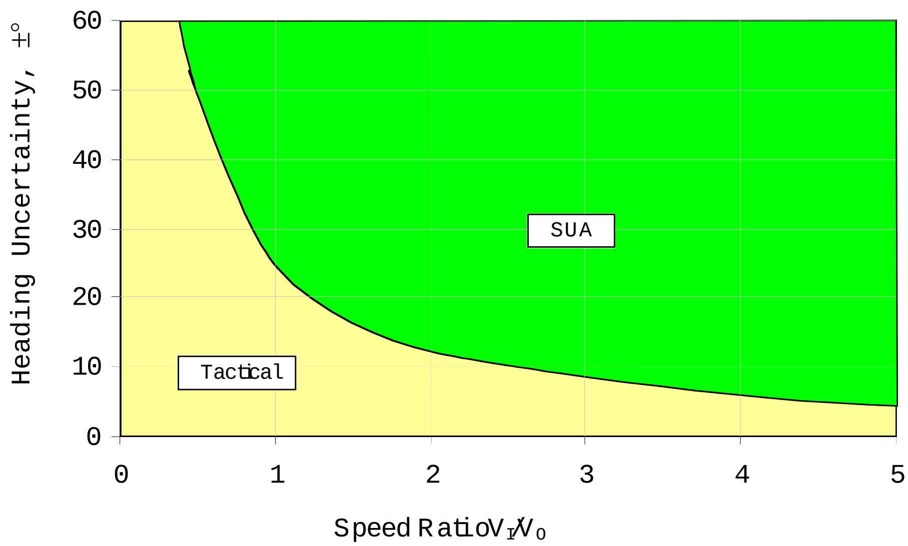

Figure 38: SUA Tactical trade-off Example (head on)
(30° turns, 60NM SUA)

The same procedure can be employed with other types of conflicts, but the analysis is not quite so simple. This is because the path lengths for left turn and right turn avoidance maneuvers are different, and need to be optimized to ensure a fair comparison. In addition, speed change for non-parallel cases causes angular change in the alert zone geometry, which further complicates matters.

5 Human Factors Issues

The current air traffic management system has been developed through an evolutionary process in which there are a number of vehicles with similar performance characteristics. Dissimilar vehicle characteristics are often separated naturally by altitude, and conformance to similar performance is enforced in certain airspace (e.g., maximum airspeed of 250 kt below 10,000 ft). Unconventional vehicles or mission profiles (e.g., space launches or military training) are generally separated using SUA due to the difficulty in providing separation using conventional traffic vectoring methods. In order to separate high-speed, potentially low-maneuverability vehicles from conventional air traffic without the use of SUA, additional decision aids for air traffic controllers and mission controllers will be needed.

In particular, aircraft are typically separated by segregating traffic by altitude according to direction of flight, and then by providing in-trail separation between aircraft at the same altitude. Vertical control is typically effected by issuing climb or descent clearances in which a block of airspace is cleared. This allows flexibility in the specific performance of the aircraft between leaving the previous altitude and capturing a newly assigned altitude. As vertical rates increase, this type of control will become more difficult unless additional controller aids are provided. These aids would help controllers better determine what airspace will be used by vehicles that are climbing or descending by providing more accurate trajectory predictions and conflict detection tools.

Conflict detection and resolution tools for air traffic controllers are currently being developed by the FAA and NASA. These tools are designed to aid controllers in predicting conflicts and in resolving them efficiently, and are an initial step in providing the capability for aircraft to follow user-preferred trajectories. Two such tools are currently being developed and evaluated, and serve as a starting point for planning tools for use with RLVs. The User Request Evaluation Tool (URET) is being developed by MITRE, and alerts controllers to predicted conflicts based on flight plan information [20]. Conflicts with SUA may also be predicted. URET also allows the controller to evaluate alternate routings, by specifying new altitudes, speeds, or waypoints.

The Center-TRACON Automation System (CTAS), under development at NASA Ames Research Center, is a tool-suite with modules to aid in detecting and resolving conflicts, and for sequencing aircraft [21]. CTAS provides conflict advisories, and allows a controller to interactively evaluate alternate flight plans using arbitrary (non-navaid-fixed) waypoints.

Both URET or CTAS (or a follow-on set of tools) could be modified to also provide conflict detection and resolution capability for Space Transition Corridors (STC). This would require modifying the minimum separation requirements between vehicles so that conflicts with a STC can be detected and resolved safely and efficiently. Additionally, new display capabilities would be required in order to depict the STC in a manner that is useful to the air traffic controller.

Additional research into display requirements to enable STC-based traffic management is needed. This includes examining both display characteristics (e.g., symbology, or the ability to depict the vertical profile of a STC), display logic (algorithms used to detect and resolve conflicts), and control of information (e.g., state information on the RLV, and the planned trajectory). Recommendations for further human factors study are provided in Section 6.

6 Conclusions

The geometry of the Alert Zone gives us an approximate measure for the area that needs to be observed for a given avoidance strategy. The geometry drives the sensing and observation requirements and gives conflict duration information. We can determine the alert zones for the expected types of intruders and their flight phases. Different classes of intruders such as air breathing engine powered RLVs, or shuttle type RLVs, will require different alert zones for the phases of flight they may be in (e.g. takeoff, cruise, or landing). The union of the expected subset of these alert zones will be the volume that needs to be observed. Once an intruder from one of the expected class enters this volume, a decision would be made as to whether an avoidance maneuver needs to be taken. The selection of the type and severity of avoidance maneuver will also be determined at this time, if more than one option is available.

The characteristics of the intruder, such as performance and predictability are also important drivers. The sensory capabilities in turn can also drive the avoidance strategy. As more reliable and accurate information becomes available, the safety margins can be reduced while maintaining the safety level. Emerging sensory technologies are allowing radical improvements in tracking and communications. However, it may not be so easy to improve the predictability of vehicles guided by non-deterministic systems such as humans.

We formulated a strategy for comparing RLV operating modes employing SUA concepts, against tactical one-to-one avoidance mode concepts. The maneuvering costs in time and distance associated with these avoidance maneuvers were briefly discussed, with techniques for minimizing them for given encounter geometries. The above overview addressed the conflict avoidance issues that need to be considered to evaluate the desirability of integrating RLV operations into the air traffic system. We have compared conflict avoidance options using measures of alert zone size and deviation from track.

6.1 Contributions

We developed a geometrical technique for determination of Alert Zones, based upon maneuvering capabilities of aircraft, intruder characteristics, and separation requirements, allowing detailed analysis. A tool to mechanize the computation of Alert Zone geometry as function of encounter geometry, speed, maneuverability, heading and sensor uncertainty, and other variables was developed. Parametric studies were performed to evaluate sensitivity of Alert Zones to factors such as turn rate, turn magnitude, speed, and heading uncertainty. Comparisons were made between horizontal and vertical Alert Zones to determine the domains in which each type of maneuver was effective. It was found that climb alone could not be used to resolve conflicts with an intruder descending at 10,000 ft/min (e.g., Space Shuttle) without climbing more than 4000ft.

Preliminary analysis of required traffic deviation as a function of trajectory uncertainty was used to compare impact of SUA to tactical conflict resolution for head-on conflicts. This allowed initial partitioning of when SUA is appropriate and when tactical avoidance is appropriate. For example, for equal speeds and uniform distributions of traffic, it was found that up to ±24° heading uncertainty could be accepted for tactical resolution before a 60NM diameter SUA became the more efficient solution.

6.2 Recommendations for Future Work

6.2.1Modeling

Conflict avoidance models should be integrated with traffic models to estimate true traffic flow penalties, and system-wide costs. The effects of more complex trajectories, such as those with changing speeds and headings, which often exist in real-world conflicts, need to be analyzed. The basic conflict analysis developed in this work can be extended to other types of avoidance maneuvers, which could then be integrated with the traffic impact and cost models to provide a more complete picture. Displays and procedural requirements, in addition to human factors issues, also need to be examined.

Work in Phase III will focus on developing the tools shown in Figure 39. To date, a Conflict Model has been developed, which allows for parametric studies between vehicle performance, uncertainty, maneuverability, and encounter geometry, and outputs the required Alert Zone size. This model must then be exercised to determine the requirements that must be satisfied for each of the modes of operation under consideration. This begins by determining how conflict encounter situations change as a function of RLV type and characteristics. Thus, a model is required to determine typical state values and uncertainties for a selected set of RLV types and mission profiles. This information is then used to determine the required Alert Zone size. When coupled with an Airspace Model which includes traffic density and traffic mix, expected conflict alert rates and incurred delays can be estimated. This information can then be compared against similar data obtained by Virginia Tech through its studies on SUA operations. The resulting capability will allow for the development of requirements on vehicle equipage and controller facilities in order to enable tactical modes of operation that are at least as safe and efficient as the use of SUA. Additionally, efforts will focus on the tradeoffs and requirements for Tactical Control and Space Transition Corridor control.

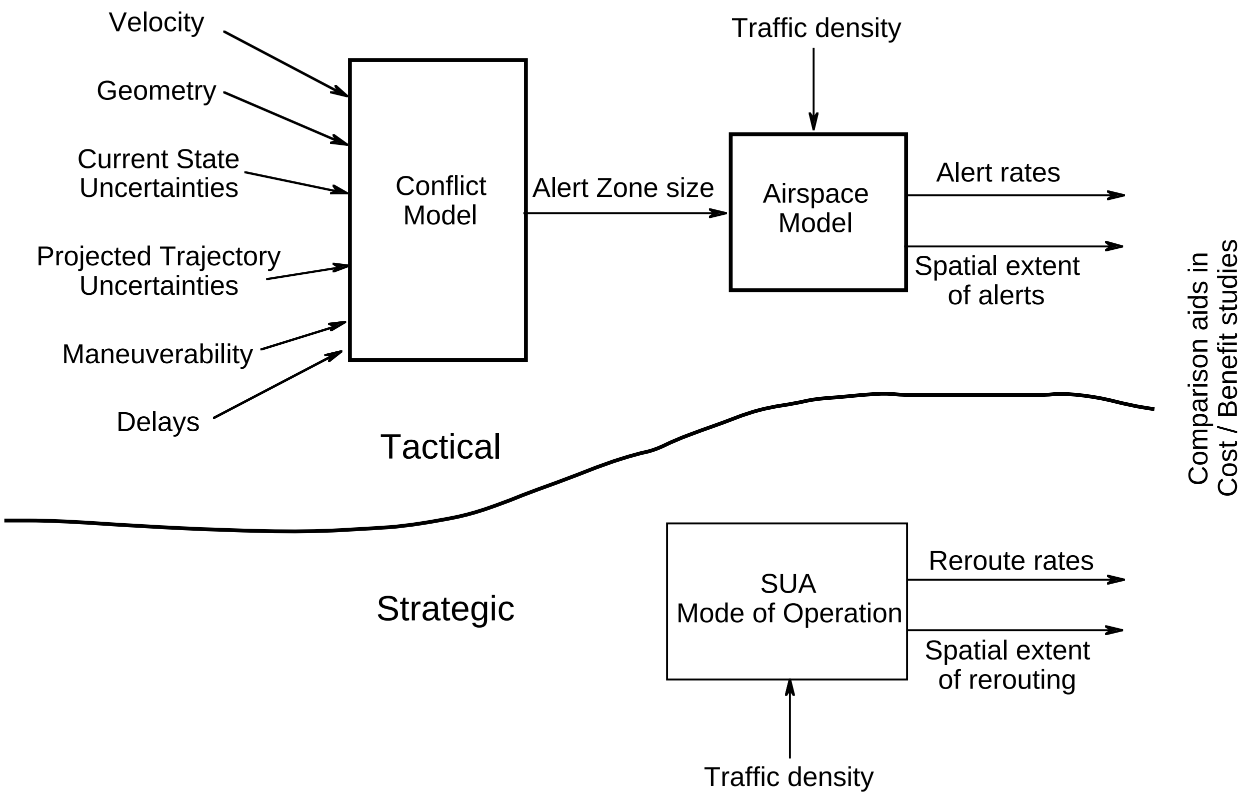

Figure 39: Modeling Tools in Phase III

6.2.2Human Factors Evaluations

Recommendations for further human factors evaluations are divided into three major areas: displays, procedures, and information flow.

In terms of display evaluations, studies are required to develop potential enhancements to current and future controller displays to aid in visualizing SUA or Space Transition Corridors (STC).

SUA is a static region of airspace and so is more easily displayed. STCs, however, may be transient, shape-changing, moving regions of airspace. Research is required to develop prototype displays that convey the spatial (horizontal extent and vertical extent) and temporal aspects of the STC. Constraints on STC behavior (e.g., rate of shape change or movement) may need to be set due to human-factors limitations. Additionally, tools are required to aid controllers in detecting aircraft conflicts with the STC, and in resolving those conflicts when they occur. Some type of conformance monitoring or feedback may also be required to ensure that the RLV is inside its STC.

Additional display research is required for tactical control concepts. Current work in conflict detection and resolution is focusing on conventional aircraft that fly waypoint-based flight plans. RLVs have different performance characteristics, and may follow trajectories that are not as easily described as a list of waypoints. The additional display features that would be required in order to enable controllers to separate traffic from RLVs must be evaluated.

New procedures also need to be developed to facilitate controller-to-pilot and controller-to-space mission control interactions. This may require new high and ultra-high altitude sectors and their coordination requirements. Additional clearances and phraseology may also be required (e.g., “cleared for the STC reentry”).

Finally, improved information flow will be required between aircraft, RLVs, air traffic control, and space mission control. This may place additional burdens on pilot and controller workload that must be managed through decision aids and displays. Requirements for information accuracy and recency must also be defined. Appropriate roles and responsibilities also need to be determined. For example, it is unclear what role air traffic control should take in monitoring RLV conformance to a defined flight profile, and to what degree that function should be assigned to space mission control. Conceivably, if the RLV is managed using tactical control, then air traffic control would need to monitor the RLV's flight path; if the RLV is managed using a STC, then it may be more appropriate for the space mission controller to monitor conformance. Procedures for informing air traffic control of a deviation, however, also must be defined.

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8 Appendix

8.1 Maneuver based limits: Methods and Tools

8.1.1Preliminaries

The instantaneous projected miss distance in a typical conflict can be determined from relative velocity and relative position. Resolution is required if the miss distance is less than the minimum and the intruder is not expected to change its velocity. We are able to change the ownship velocity vector in direction (heading and altitude rate) and length (speed). To select maneuvers we compare the gain in miss distance to the loss in performance in the general sense (such as reduction in velocity towards the next flight waypoint, or increase in total fuel consumption due to non-optimal altitude). Altitude rate and speed have upper and lower limits based on the performance characteristics of the aircraft while allowable heading change may be limited by the penalty it imposes on mission effectiveness.

The change in miss distance obtained is a product of range and the difference between sines of the original and final angles between the relative position and relative velocity vectors (r and r´). The rate of change of r with change in heading or speed is thus an important parameter in determining the effectiveness of the candidate maneuvers (Figure 40).

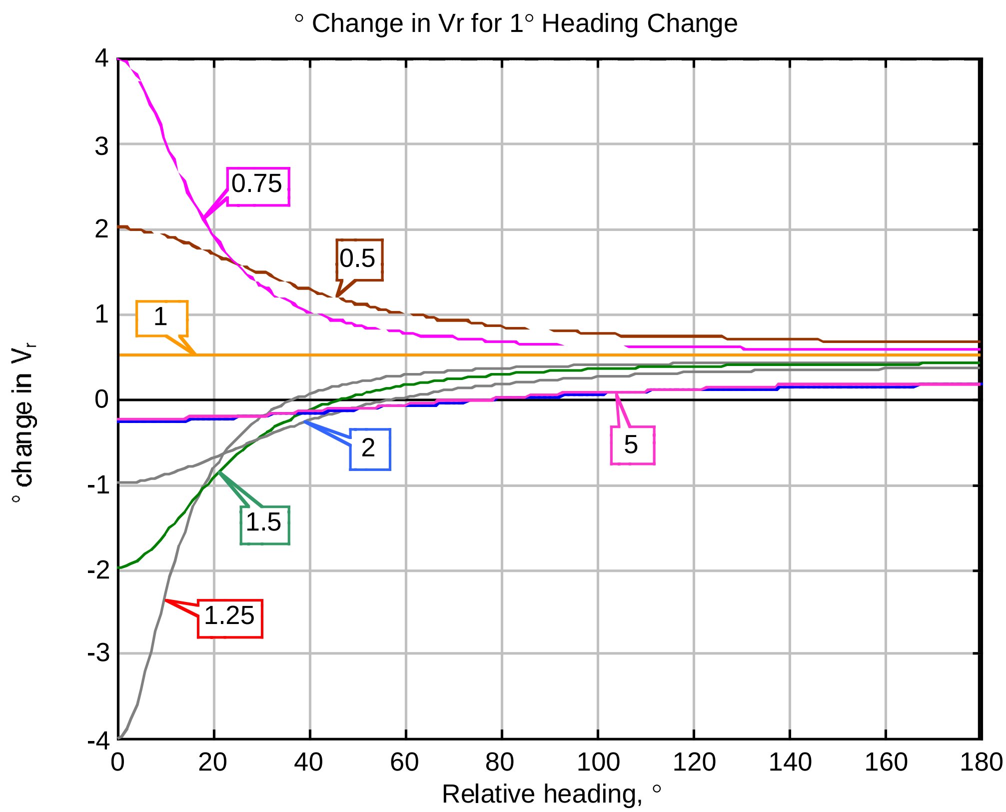
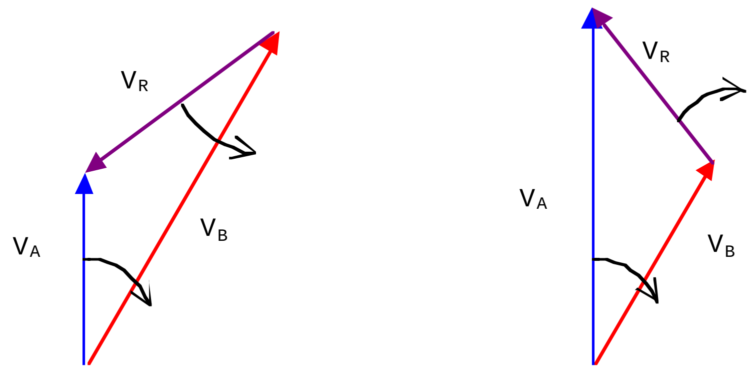


Figure 40: Effectiveness of Heading Change, ° change in V_r per ° change in Heading

As the aircraft turns both the angle and length of relative velocity vector change. If aircraft B is slower than A then the change in angle always has the same sign as the heading change. However if B is faster than A a sign change occurs at:

$$r = \cos^{-1} (V_A/V_B)$$

If the original difference in headings is smaller than this value, the change in heading is of opposite sign (Figure 41).



Velocity ratio, $V_B/V_A > 1$	Velocity ratio, $V_B/V_A < 1$
Relative heading < Critical: V_A Clockwise, V_R Counterclockwise Relative heading > Critical: V_A Clockwise, V_R Clockwise	V_A Clockwise, V_R Clockwise

Figure 41: V_R Rotation Direction

The total angle change is given by the integral of the appropriate curve in Figure 40 from the initial to the final heading angle. If the turn is one over a finite time period there is an additional change due to the relative velocity. If angles are measured from the original PCA the calculation becomes simplified as the changes in angle due to this effect become zero as does the original angle.

Heading changes become progressively less efficient overall as B's velocity increases. In addition on the curves for velocity ratios greater than one their are further difficulties in regions near the sign changes. If the initial angle is at the sign change the relative angle changes in the same direction irrespective of whether the turn is to the left or right. The direction changes as you cross the zero points and the already achieved change is negated

As a result for velocity ratios greater than one there are certain heading difference angles for which a given turn angle gives no change in relative velocity angle, or both right and left turns give same change (Figure 21).

Figure 42 shows the rate of change in relative angle with percent change in speed. The effect is generally poorer than heading change. However as speed change is at right angles to heading change it remains effective at the points where direction change becomes weak. The desirable crossover points depend on the the performance characteristics and objectives of A.

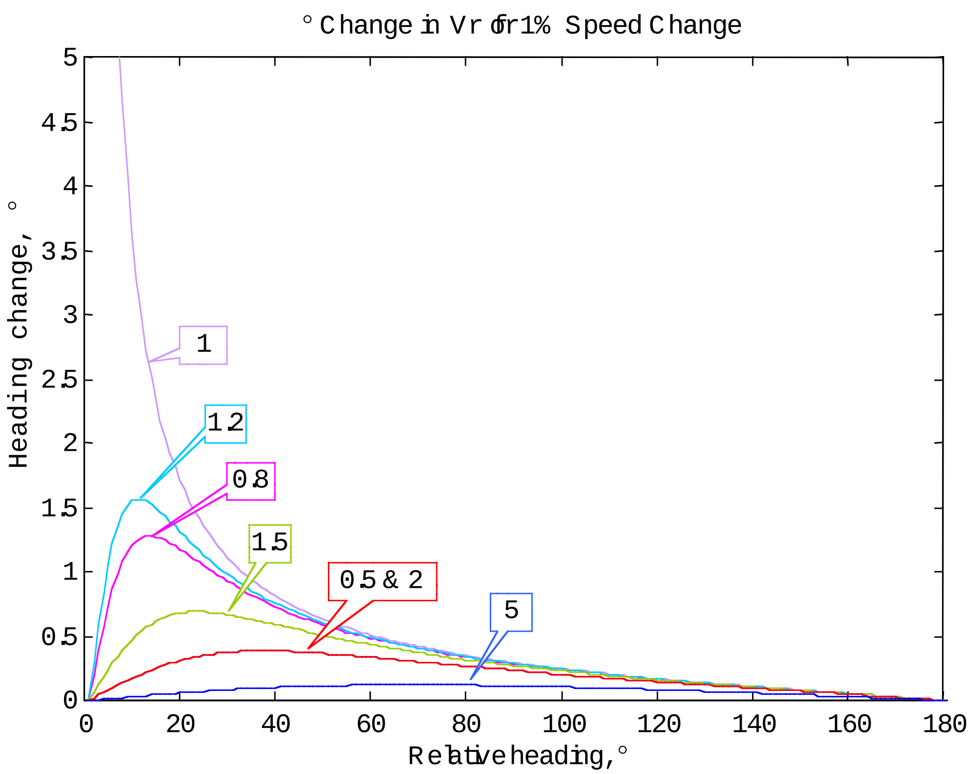


Figure 42: Effectiveness of Speed Change, ° change in V_r per % change in speed

In general, ownship velocity changes along the direction of relative velocity are ineffective.

The boundary at which the resolution sequence must be initiated depends on:

1. Required separation
2. Maneuver delay
3. Allowed turn rate
4. Allowed turn angle

INITIAL DELAY

The delay between detecting the intruder crossing the Alert Zone boundary and starting the maneuver is highly variable, depending upon whether the alerting is performed by an onboard system or by a ground based system. Ground based systems are subject to delays in communication and acknowledgement that the onboard systems are not. In what follows a delay of 20 seconds is assumed in general. The turn initiation time is also included in this figure. Figure 43 shows the components of delays over a notional timeline.

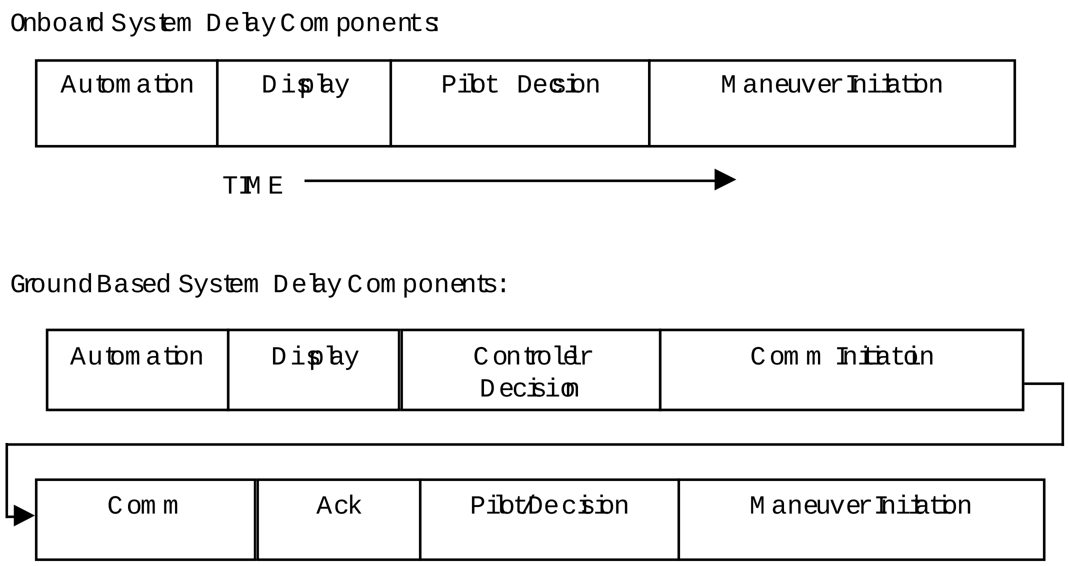


Figure 43: Notional Initial Delay Components

In comparisons with current primarily human based ATC, the alerting is typically performed even earlier and the practical protected zone is enlarged (e.g. to seven NM versus the required five). The controller cannot be fully assured that the pilots will maneuver at the expected value and will compensate for these less severe maneuvers.

TURN

For any bank angle, the turn radius and rate are dependent upon the speed For a given bank angle in a level turn the lateral acceleration, a_H, is given by:

$$a_H = g \tan \theta$$

where g is the acceleration due to gravity and θ is the bank angle.

The turn radius, r, is then:

$$r = v^2 / a_H$$

where v is the velocity in the appropriate units. Thus for an aircraft in a 30° bank travelling at 450 knots the turn radius is 5.1NM and the turn rate is 1.40°/s.

STRAIGHT TRAVEL TILL PCA (POINT OF CLOSEST APPROACH)

Once the maximum turn angle is achieved the turn is complete and the wings are leveled. Straight-line travel on the new heading continues until the point of closest approach (PCA) is passed.

RETURN TO ORIGINAL HEADING OR ORIGINAL TRACK

After PCA the aircraft are diverging and the original heading can normally be resumed or if desired the aircraft can be returned to the original track. Any combination between these extremes can also be selected depending upon the distance to the destination and local traffic conditions.

VARIABLES

General

τ_D Maneuvering Delay

V_A Ownship Velocity

V_B Intruder Velocity

Relative heading

Horizontal

Protection Zone (PZ) Radius

Turn Radius

Maximum Turn Angle

Vertical

Protection Zone Height

Ownship Altitude

Intruder Altitude

Ownship Vertical Rate

Intruder Vertical Rate

Maximum Vertical Rates

Altitude Limits

Maximum pullup/pulldown load factors

8.1.2 Determine the Relative Path

The path followed by A in earth relative coordinates is drawn. We don't know a priori how long the changed heading will be needed. The absolute path is then transformed to get the path in the frame moving with the intruder B.

We show this in Figure 44. The vehicles A (ownship, 450kt) and B (Intruder, 450kt) are travelling at a relative heading of 180°. The delay is assumed to be 20s. The maximum turn rate is 1.4°/s (30° bank angle) and the turn is limited to 45°.

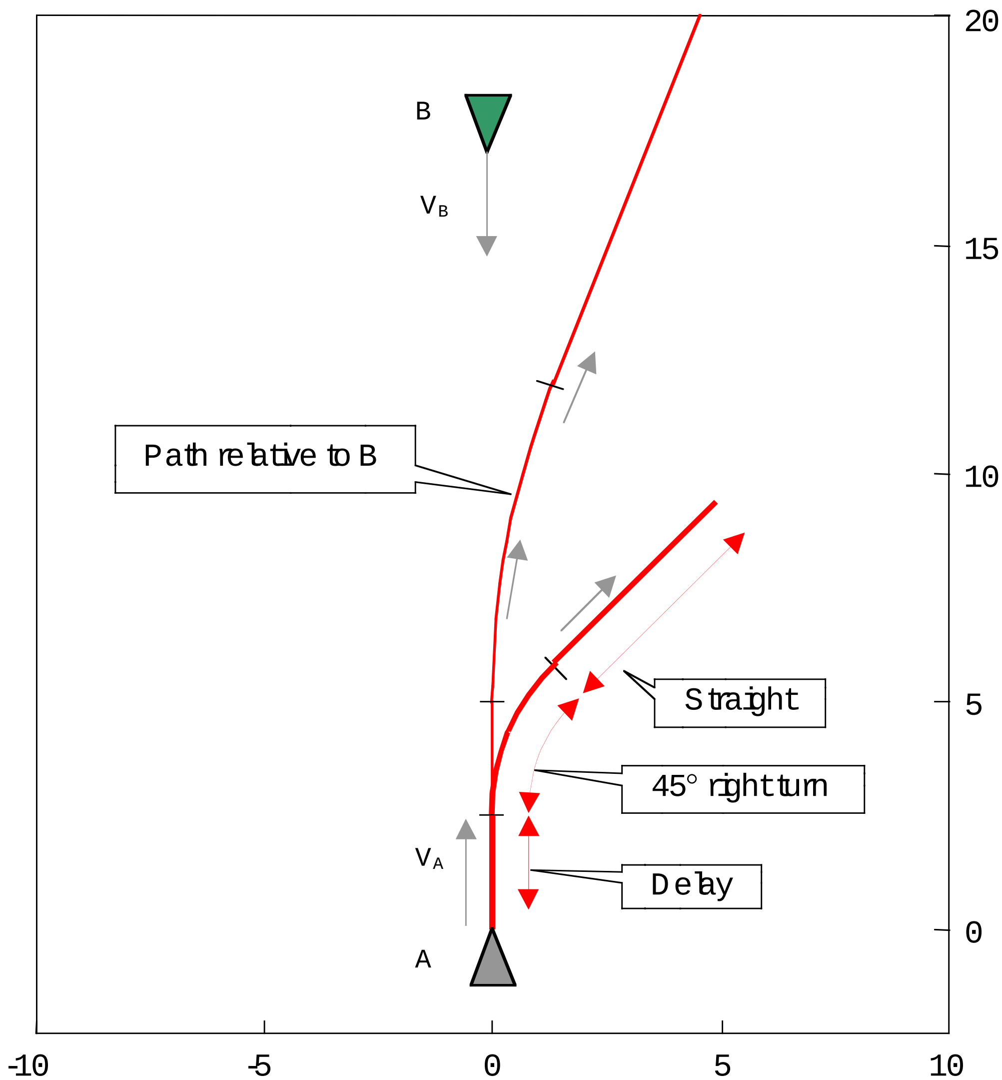


Figure 44: Determine the relative path

8.1.3Determine the Boundary

Once the relative path has been determined the protected zone (PZ) is swept along it and the boundary defined by the edge in the opposite direction to the turn is obtained (Figure 45). The avoidance maneuver sequence must be initiated at this boundary to avoid penetration of the PZ.

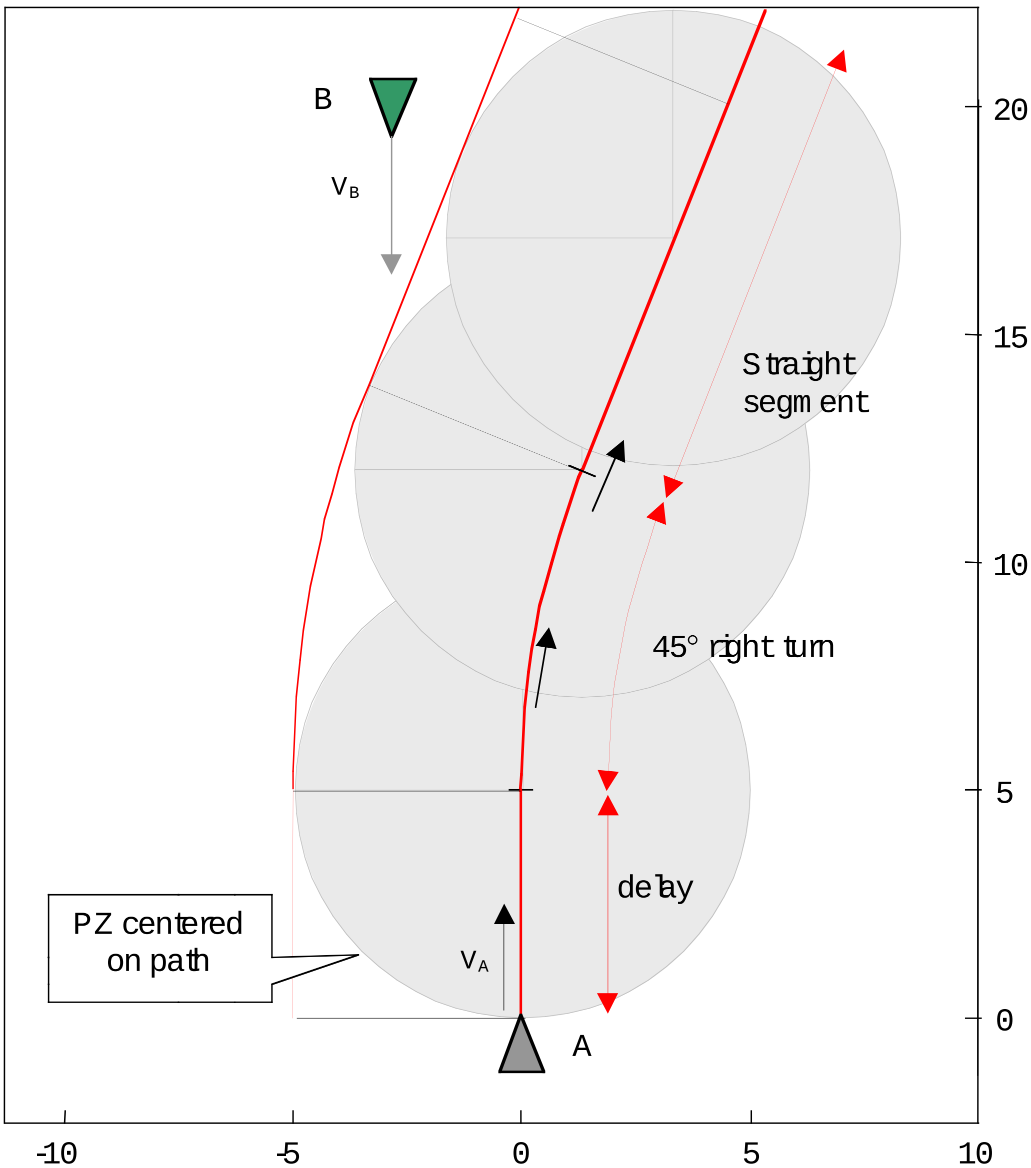


Figure 45: Sweep PZ along relative path to get the boundary

8.1.4Combine Right and Left Boundaries to get Alert Zone

The same procedure is followed for the other allowed maneuver. Here we are allowed to turn left as well and the second boundary is obtained to the right. The Right-Turn and Left-Turn Boundaries are overlaid to get the required alert zone (Figure 46). The crossover point is the intersection of the two boundaries at the apex of the triangular alert zone.

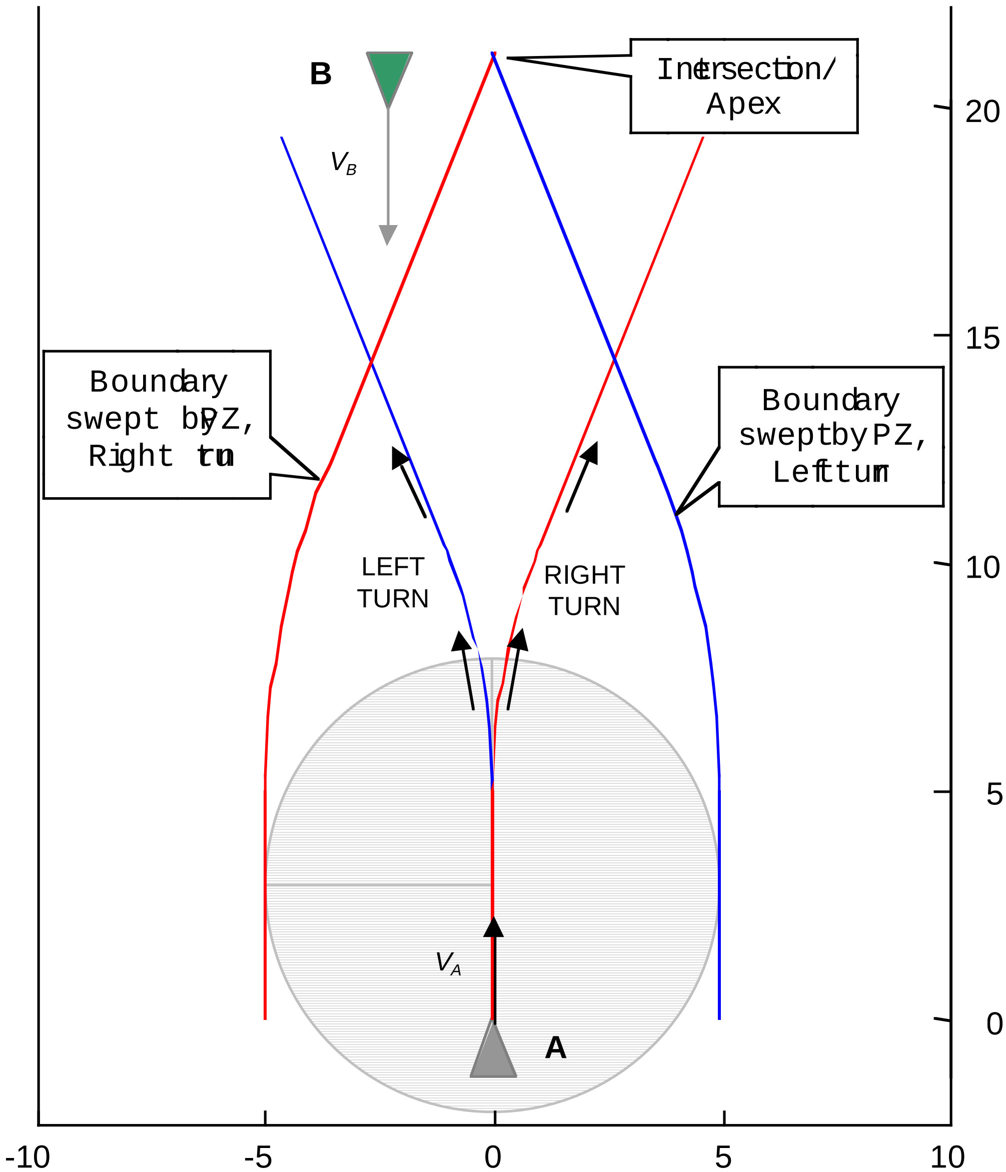


Figure 46: Combine the boundaries

8.2 Modeling Uncertainty

8.2.1 Uncertainty Components

We can model position uncertainty as a volume centered on the measured or reported position.

The protection zone can be drawn from all the points enclosed in this volume and the enlarged combined volume is obtained (Figure 24). The combined volume can then be used to determine the alert zone in place of the PZ in Figure 45. The uncertainty in velocity vector is typically of magnitude and direction. The relative velocity vector is affected by both depending upon the nominal relative heading. As shown below we can determine alert zones for all the possible combinations of speed and direction error and find the limiting zones to guarantee successful avoidance.

8.2.2 Guaranteed Avoidance with known Uncertainty

As an example we show a case for which the relative heading angle range is 180° ±10° and, the velocities V_B=V_A=450kt. The turn angle is 45°, and the turn rate is 2°/s. The extremes of relative heading angle are 170° and 190°. The alert zone and swept areas for left and right turns of 45° are shown in Figure 47 for 170° and Figure 48 for 190°. Overlaying both of these, and extending and connecting the boundaries the enlarged zone shown in Figure 49 is obtained.

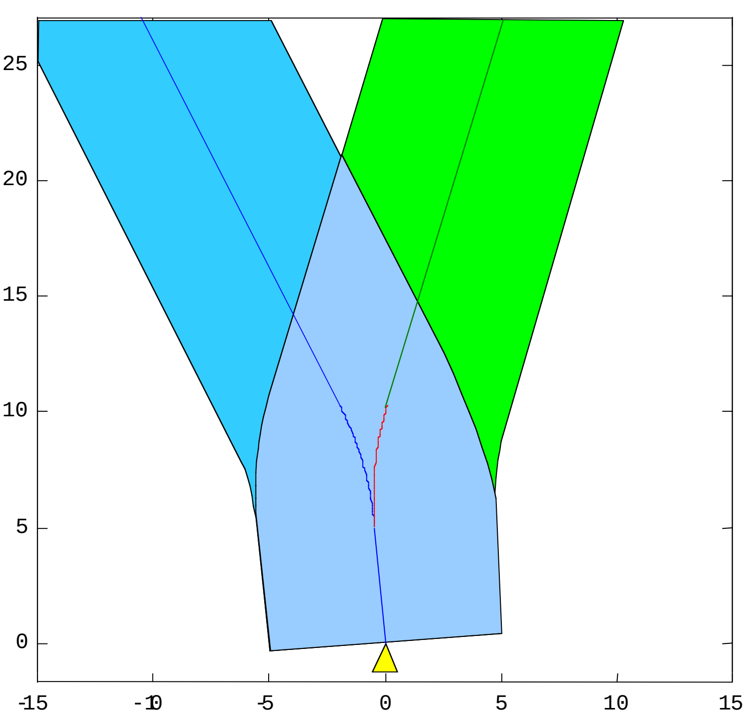


Figure 47: 170° swept areas

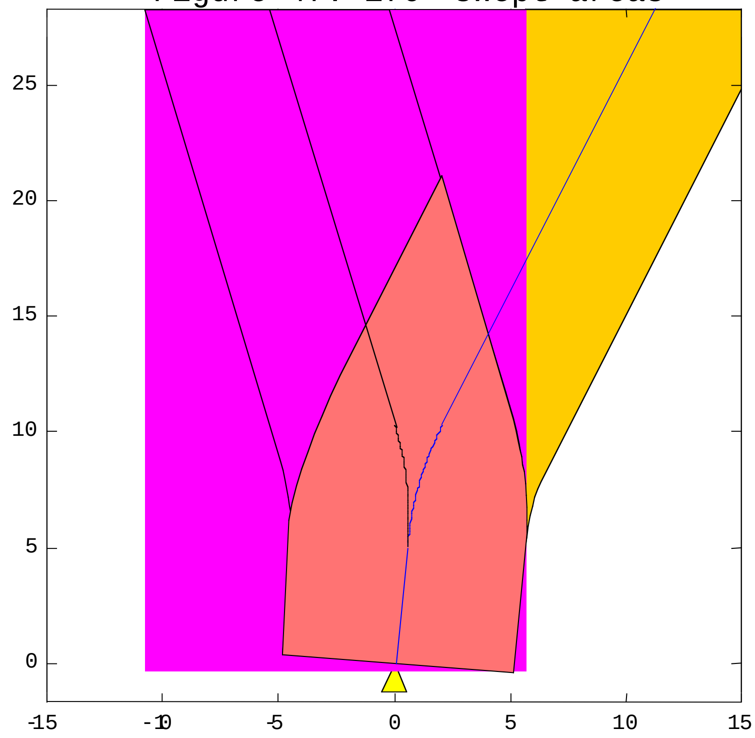


Figure 48: 190° swept areas

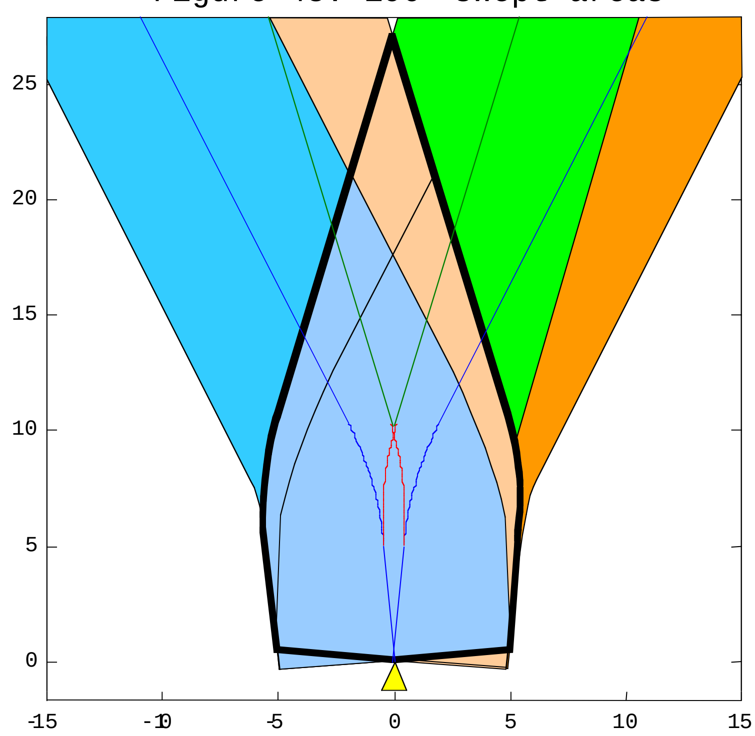


Figure 49: Combined swept areas

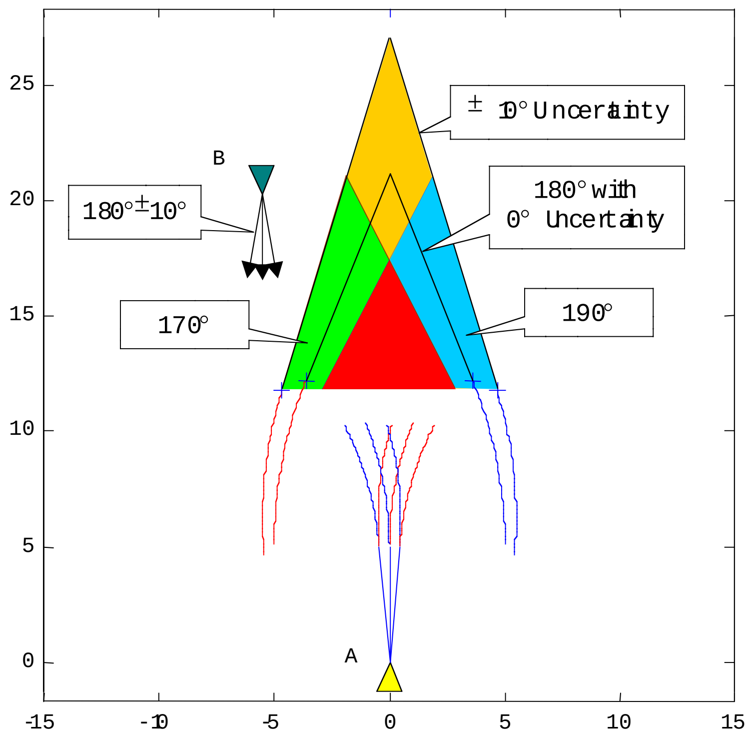


Figure 50: 180°±10° alert zone compared with 180°±0° alert zone

It is clear that as uncertainty increases the alert zone becomes longer and longer till the limit of uncertainty becomes equal to the allowed avoidance turn. Then the sides of the combined alert zone become parallel and its length becomes infinite. Then, should the intruder appear within this zone no matter how far away, avoidance cannot be guaranteed unless the maneuver limitations are removed. For uncertainties larger than the allowed turn, the alert zone becomes linearly divergent.

Figure 51 illustrates the increase in apex distance for the combo alert zone, with increasing uncertainty for various speed ratios Trajectory uncertainty has little impact for speed ratios <<1, and impact increases as speed ratios become larger. The distance goes to infinity for speed ratios greater than one at uncertainties lower than the allowed turn angle (45° here). The angle at which it goes to infinity is given by (head on case equating the sideways speeds for A & B):

$$\theta = \sin^{-1}(V_A \sin(45°) / V_B)$$

For $V_B/ V_A = 2$, $\theta = 20.7°$, and for $V_B/ V_A = 4$, $\theta = 10.2°$.

Figure 52 shows the same data on speed ratio and Apex distance axes. Alert distance is again seen to be increasingly sensitive to both relative speed and uncertainty.

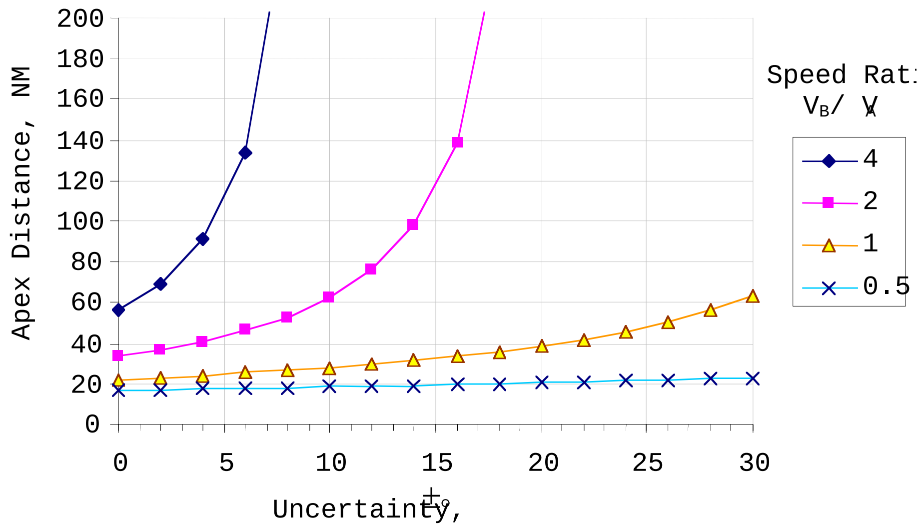


Figure 51: Apex Distance vs. Uncertainty for Speed Ratios (head on, 45° maximum turn)

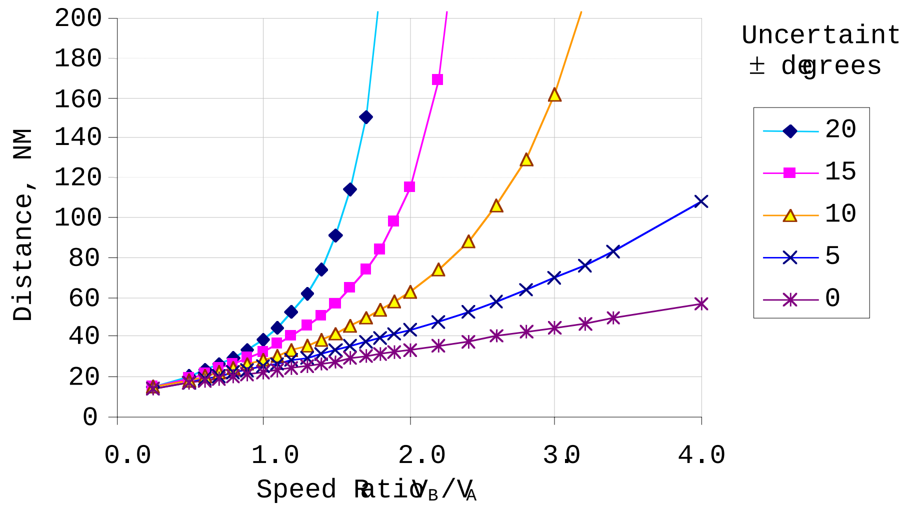


Figure 52: Apex Distance vs. Speed Ratio for heading uncertainty

The distance the Apex is from the ownship is a convenient index for determining the difficulty level of the conflict and the efficacy of the selected avoidance maneuver. Figure 53 shows the variation in apex distance with increasing allowed maximum turn angle for the head-on (180°) case. The maximum bank angle is limited to 30° giving a turn rate of 1.4°/s. Curves for velocity ratios (V_B/V_A) of 4, 2, 1, and .5 are shown.

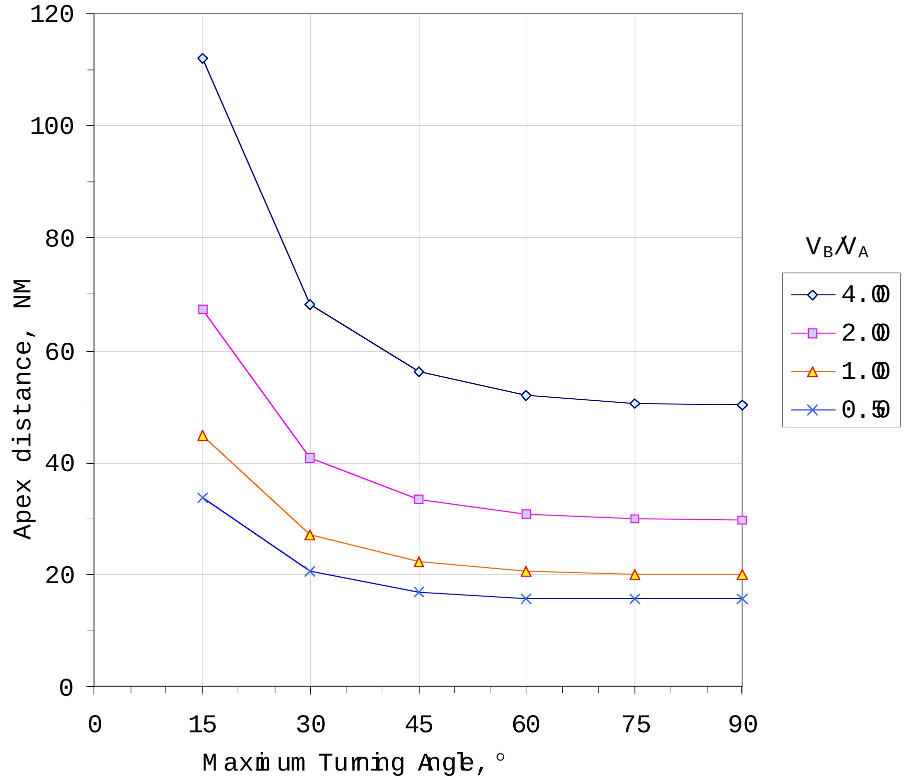


Figure 53: Apex Alerting Distance vs. Maximum Turning Angle (head o

The marginal benefit decreases with increasing turn angle. It goes to zero at the angles shown in Table 3 as the left turn and right turn boundary curves meet (shown in Figure 11 for V_B/V_A=1 only). The turn could be continued beyond this but the point of closest approach (PCA, for an intruder starting at the apex, the worst case) has been passed and any more turning is pointless.

Table 3: Maximum turn angles to close the Alert zone

V_B/V_A	4	2	1	.5
Maximum useful turn angle (at PCA for Intruder initia	86	82	76	69