

Safety Analysis of TCAS on Global Hawk using Airspace Encounter Models

by

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B.S., Aeronautical Engineering (2004)

United States Air Force Academy

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Aeronautics and Astronautics

at the

Massachusetts Institute of Technology

June 2006

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Report Documentation Page			Form Approved OMB No. 0704-0188		
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 01 JUN 2006		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Safety Analysis of TCAS on Global Hawk using Airspace Encounter Models				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Massachusetts Institute of Technology				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFIT/CIA, Bldg 125 2950 P Street WPAFB, OH 45433				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 66	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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Abstract

This work is sponsored by the Air Force under Air Force Contract #FA8721-05-C-0002. The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

The U.S. Air Force's RQ-4 Global Hawk unmanned aerial vehicle (UAV) is a high altitude, long endurance aircraft used for surveillance and reconnaissance. Because of the potential for close proximity to manned aircraft in civil airspace, collision avoidance is a major concern, and the Air Force is seeking to equip Global Hawk with the Traffic Alert and Collision Avoidance System (TCAS) to reduce the probability of mid-air collision. Currently, Global Hawk is equipped with a Mode S transponder and uses chase aircraft, ground observers and/or ground radar contact to comply with the collision avoidance requirement.

In order to evaluate TCAS effectiveness, a fast-time simulation tool has been developed at MIT Lincoln Laboratory that computes the mean probability of a near mid-air collision for a large number of close encounters between two aircraft. Airspace encounter models enable sets of encounters to be simulated that are statistically representative of the aircraft encounters that actually occur in the airspace. The TCAS logic is implemented in the simulation tool and the aircraft responses during the encounters, with and without TCAS, are simulated in parallel. By observing measured vertical miss distance at the closest point of approach between the two aircraft, it is possible to quantify the reduction in collision risk provided by TCAS, termed the risk ratio.

Global Hawk's flight characteristics differ from a conventional aircraft. Its mission profile through civil airspace includes slow, steep climbs and descents, and shallower turns than a conventional aircraft. Its vertical acceleration and climb rate limits can hinder its response to a TCAS resolution advisory (RA). Communication latency also may occur. For this thesis, encounter models were developed that reflect Global Hawk's flight characteristics. The new encounter models were then implemented in the simulation tool, and millions of encounters between Global Hawk and a conventional aircraft were simulated. These encounters were compared against encounters between two conventional aircraft to observe how Global Hawk's flight characteristics changed the effectiveness of TCAS.

Assuming a standard pilot response to TCAS RAs, TCAS provided a significant safety improvement to Global Hawk over a Mode S transponder alone, yielding risk ratios in the range of 0.003 to 0.079. Global Hawk's flight characteristics generally caused a decrease in TCAS effectiveness from the original encounter models. Encounters were also simulated where Global Hawk's response to TCAS RAs was delayed by increasing amounts to simulate communication latency. A delay of approximately 15 seconds was tolerable before TCAS provided less safety than a Mode S transponder alone.

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List of Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	Airborne Collision Alerting System Analysis
ACC	Air Combat Command
AFB	Air Force Base
ATC	Air Traffic Control
CPA	Closest Point of Approach
COA	Certificate of Waiver or Authorization
FAA	Federal Aviation Administration
HMD	Horizontal Miss Distance
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
KCAS	Knots Calibrated Airspeed
KTAS	Knots True Airspeed
NAS	National Airspace System
NMAC	Near Mid-Air Collision
RA	Resolution Advisory
ROA	Remotely Operated Aircraft
SCRSP	Surveillance and Conflict Resolution Systems Panel
TCAS	Traffic Alert and Collision Avoidance System
UAV	Unmanned Aerial Vehicle
VMD	Vertical Miss Distance
VSI	Vertical Speed Indicator

Acknowledgments

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I would like to thank MIT Lincoln Laboratory Division 4, under the leadership of Dr. Bob Shin, for supporting my research during my two years here. I would also like to extend my appreciation to Group 42, Air Surveillance Systems, under the direction of Jim Flavin, for the research assistantship opportunity. My experience at Lincoln Laboratory has been thoroughly enjoyable. I heard it said that there was an “expert for everything” here at Lincoln, and I found that to be true as I researched and wrote this thesis.

I want to extend my heartfelt appreciation to Dr. Jim Kuchar, Assistant Group Leader of Group 42, for his patience, insight and guidance as my thesis supervisor throughout my time here at the Lab. The learning curve was steep, but you made sure I was onboard and up to speed before diving into the project. The feedback you gave during my research and thesis writing process was timely, reliable and very helpful in producing quality work. Thank you for the time you invested to ensure that I receive excellent advice and support.

I also want to thank Val Heinz of Group 42 for the well-informed advice he gave me as I selected a topic for research and completed this thesis. I appreciate your taking the time to help me even as you were switching groups.

Numerous members of the Group 42 staff assisted me while I researched and wrote this thesis. In particular, I would like to thank Brian O'Donnell, Kathy Sinclair, Maggie Herring, Ann Drumm, and Barbara Chludzinski for their help.

My thanks go to Roger Elstun and Tee Mans at Air Combat Command, Langley Air Force Base, VA, for their sponsorship of the work that went into this thesis.

My wife's constant and loving support these past two years during my academics and research has meant so much. I appreciate your confidence in me, and I want to thank you for selflessly caring for me and for our daughter. I love you!

I am grateful to God for the opportunity He has given me to complete a portion of my education here at MIT. It has been an enriching experience which I will always remember fondly.

1. Introduction and Background

1.1. *Thesis Objectives and Approach*

The U.S. Air Force Air Combat Command is seeking to operate the RQ-4 Global Hawk unmanned aerial vehicle (UAV) in the National Airspace System (NAS) as part of its mission profile. The Federal Aviation Administration (FAA) requires UAVs to fly with an “equivalent level of safety” as that of manned aircraft [1]. Global Hawk operations are currently based on a Certificate of Waiver or Authorization (COA) issued by the FAA that requires a five-day advance notice to the FAA, along with the use of chase aircraft, ground observers and/or ground radar contact to ensure that Global Hawk avoids other aircraft. To improve operational flexibility, the Air Force is interested in using assets onboard Global Hawk to provide a collision avoidance capability. As part of this process, Air Combat Command (ACC) has been funding a study to quantify the level of safety potentially provided by equipping Global Hawk with the Traffic Alert and Collision Avoidance System (TCAS).

While numerous levels of collision avoidance protection exist, this thesis focuses only on the effect of Global Hawk’s flight characteristics and communication latency on the level of safety provided by TCAS in collision avoidance. All other effects on Global Hawk collision avoidance are assumed to be similar to manned aircraft. These effects may include procedural steps and aircraft separation provided by the air traffic management system. This thesis also does not discuss the operational flight test and evaluation that would be necessary to obtain certification to equip Global Hawk with TCAS.

1.2. *Global Hawk Collision Avoidance Requirement*

The development of unmanned aerial vehicles (UAVs), especially in the United States, has increased greatly in recent years. During the four decades of the Cold War, all but 4 of 16 major U.S. military UAV efforts were cancelled, but in the decade since, only 4 of 12 have been cancelled, and three of those have been brought back to life [2]. Several factors have caused this streak of successful UAV programs. First, highly accurate navigation is now possible due to Global Positioning System (GPS) satellites and ring laser gyros, and quicker microprocessors have expanded mission capabilities for military UAVs. In addition, decreased hostility of over-theater airspace has enabled UAVs to be utilized where they would not have been before. UAVs

have been deployed in each of the United States' last five major regional conflicts (Persian Gulf, Bosnia, Kosovo, Afghanistan and Iraq) in increasing numbers, types and roles. During the conflict in Iraq, the missions performed by UAVs included surveillance, reconnaissance, strike, target designation, diversionary decoy, and base security. Because of their success in these conflicts as well as a need for homeland defense applications, funding for UAVs has increased over the past decade and will likely continue to increase in the future.

One of the most extensively used UAVs currently in operation by the U.S. Air Force is the RQ-4 Global Hawk. The RQ-4 is a self-deploying, long-dwell, high-altitude unmanned military reconnaissance aircraft produced by the Northrop Grumman Corporation and assigned to ACC. During its limited use, Global Hawk has already passed several milestones. The RQ-4A model was deployed to both Operation Enduring Freedom and Operation Iraqi Freedom, during which it flew 16 day-long missions over Iraq and collected 25 percent of all the airborne reconnaissance imagery taken during the conflict [2]. Development has already begun on the RQ-4B, an upgraded model with an increased payload capacity and double the power previously generated onboard. With a wingspan of 116 feet and a maximum takeoff weight of 26,750 lb, Global Hawk is the largest UAV in operation by the military. The aircraft is equipped with electro-optical (EO), infrared (IR), and synthetic aperture radar (SAR) sensors for use in intelligence, surveillance and reconnaissance (ISR) [3]. The long-term plans are for Global Hawk to take over the ISR missions currently handled by the Air Force's U-2 fleet based at Beale AFB. Figure 1-1 shows a simple diagram of Global Hawk.

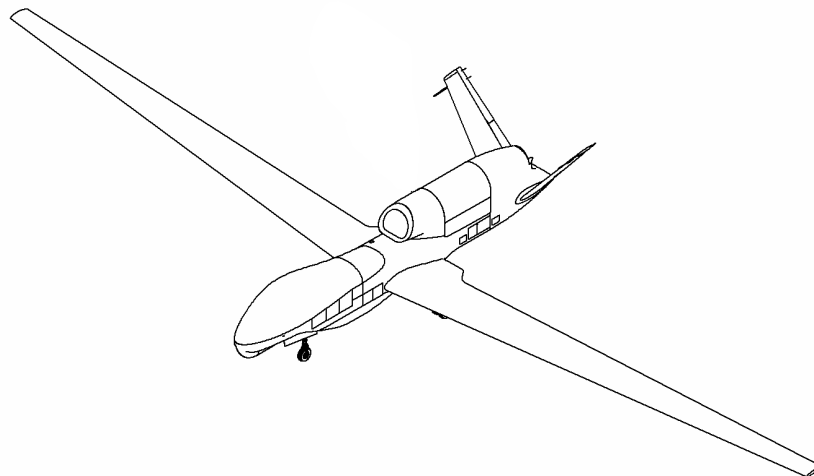


Figure 1-1: RQ-4 Global Hawk

Figure 1-2 shows a schematic of the major data links and communication networks upon which Global Hawk command and control are based. It can be seen from Figure 1-2 that Global Hawk's command and control network has numerous components. Global Hawk is operated remotely from a common ground station (CGS) which consists of a launch and recovery element (LRE), a mission control element (MCE), and supporting equipment [3].

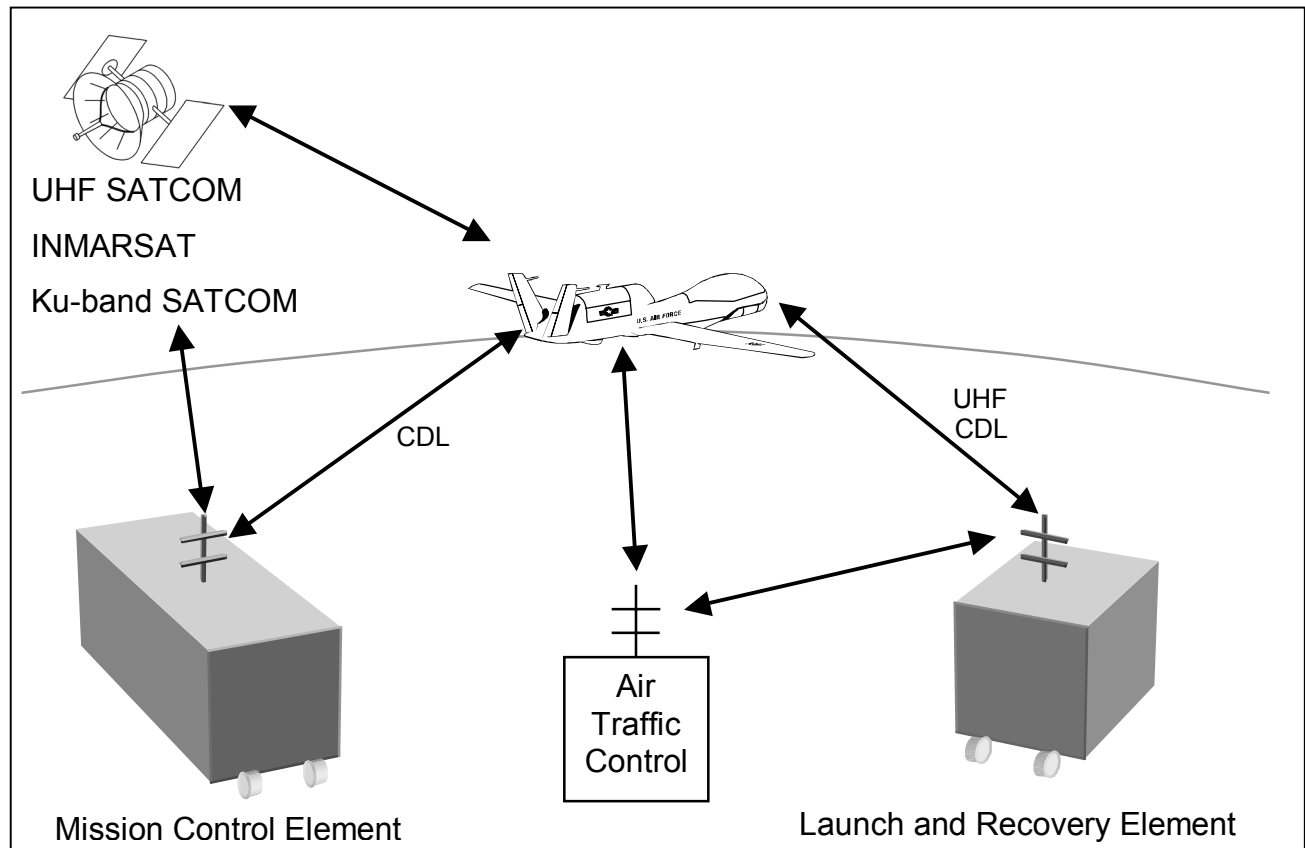


Figure 1-2: Global Hawk Communications and Data Link Networks

Command and control for Global Hawk is accomplished using both Line of Site (LOS) radio communication and beyond line of site (BLOS) Satellite Communication (SATCOM) data links. The communication system includes common data link (CDL), ultrahigh frequency (UHF) radio, International Maritime Satellite (INMARSAT), Ku-band and UHF SATCOM. Takeoff and landing are accomplished through LOS link between the aircraft and the LRE, and control is handed over to the MCE for climb, cruise, mission operations, and descent through LOS and BLOS links.

Figure 1-3 shows Global Hawk's pilot control interface from a training simulator. Global Hawk is operated using a computer mouse and standard keyboard. Therefore, the pilot is unable to directly input flight controls such as pitch and roll rate, as he would with a control stick or yoke. However, it is possible to override the preprogrammed flight plan by modifying the mission waypoints or commanding airspeed, heading, altitude or vertical velocity.



Figure 1-3: Global Hawk Pilot Interface (Training Simulator)

Global Hawk's missions may require flight operations out to 1200 miles to a mission area, up to 24 hours on-station, and then return flight to the operating base [3]. Domestically, Global Hawk is currently fielded at Edwards Air Force Base near Lancaster, California, as well as the U.S. Air Force's 12th Reconnaissance Squadron at Beale Air Force Base near Yuba City, California. Global Hawk requires flight operation in the NAS to achieve its operational

objectives, which may include transition through civil or uncontrolled airspace near its operating location. Figure 1-4 shows a map of the area surrounding Beale AFB (shown in the upper-left corner of the figure), along with example departure and arrival routings for Global Hawk. Also shown in Figure 1-4 are several points at which the aircraft would reach certain altitudes during its climb-out phase, assuming a nominal climb rate. The example routes pass through the Class C airspace surrounding Beale (the solid magenta circles in the upper-left portion of the figure), as well as in the vicinity of several other Class C, D, and uncontrolled airfields.

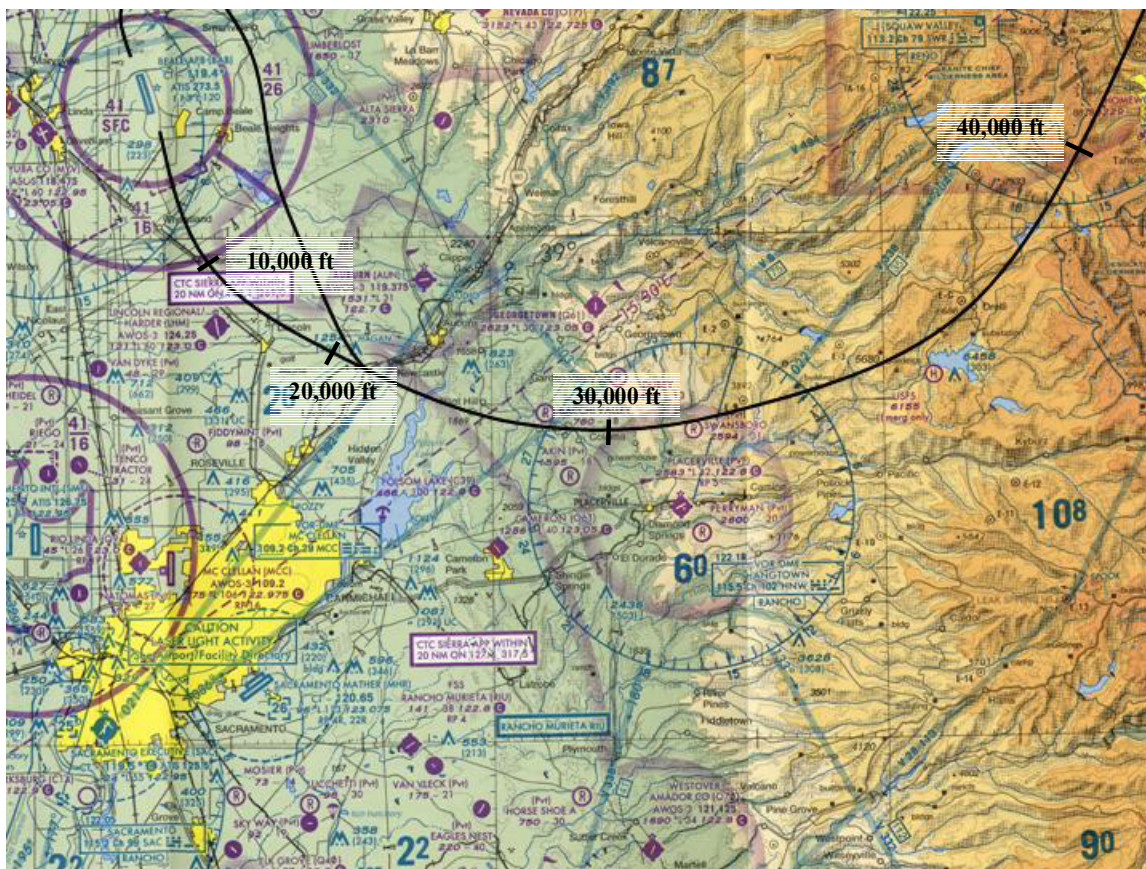


Figure 1-4: Example Arrival and Departure Routes from Beale AFB (Nominal Climb Profile Altitudes Shown)

Because of the requirement to fly through this populated airspace in the NAS, a collision avoidance concern exists for the multiple Global Hawk aircraft slated for and currently in operation.

According to FAA Order 7610.4, the U.S. military's remotely operated aircraft (ROA) flying in the NAS are required to be equipped with a collision avoidance system that provides an "equivalent level of safety, comparable to see-and-avoid requirements for manned aircraft" [1].

Various methods for unmanned collision avoidance have been considered, and include radar observation, forward or side looking electro-optical/infrared (EO/IR) cameras, electronic detection systems, visual observation from one or more ground sites, monitoring by a patrol or chase aircraft, or a combination of one or more of these methods.

Initial airworthiness for Global Hawk to fly in civil airspace was established in March 1999 through flight tests at Edwards AFB, California, and it has already flown over 5000 hours in civil airspace worldwide [4]. In August 2003, Global Hawk was the first UAV to receive a national COA from the FAA to fly routinely in U.S. national airspace [5]. Although an Instrument Flight Rules (IFR) flight plan and an emergency plan are required to be briefed to the FAA before takeoff, the COA represents significant progress in obtaining routine access to civil airspace because it shrinks the processing and approval timelines from 60 to as few as five days. In accordance with the COA, Global Hawk's operators currently coordinate all flights into the NAS at least five working days in advance with the local FAA Enroute Center [5]. Chase aircraft and ground radar are used to assist in collision avoidance, and communication is required between the Global Hawk pilot and air traffic control (ATC).

1.3. Traffic Alert and Collision Avoidance System

1.3.1. TCAS Description

A series of mid-air collisions over the course of thirty years (1956-1986) led the FAA to initiate the development and implementation of the Traffic Alert and Collision Avoidance System, or TCAS [6]¹. TCAS was developed through extensive analysis and flight evaluation, and it has served a successful role in reducing the risk of midair collisions between aircraft.

TCAS operates independently of ground-based ATC and is effective for a wide range of aircraft types. TCAS relies on the same radar beacon transponders that are used to communicate with ground-based ATC radar, and therefore cannot protect against non-transponder equipped aircraft.

TCAS operates by interrogating the transponders of aircraft in its vicinity once per second, and based on the replies received, tracks the slant range, altitude, and bearing of surrounding air traffic. Based on several replies over time, TCAS then calculates the time to

¹ Internationally, TCAS is known as the Airborne Collision Avoidance System, or ACAS.

reach the closest point of approach (CPA) with the intruding aircraft by dividing the slant range by the closure rate. If a tracked aircraft becomes a threat, TCAS issues an alert to the pilot of the equipped aircraft. Two types of alerts may be issued by TCAS: traffic advisories (TAs), which alert the pilot to an intruder aircraft and assist in the visual search for traffic, and resolution advisories (RAs), which recommend vertical maneuvers that will increase vertical separation between the two aircraft while minimizing perturbations to the existing flight path. If both aircraft are equipped with TCAS, coordinated avoidance maneuvers are performed to ensure compatibility. Figure 1-5 shows the levels of coordination provided by TCAS.

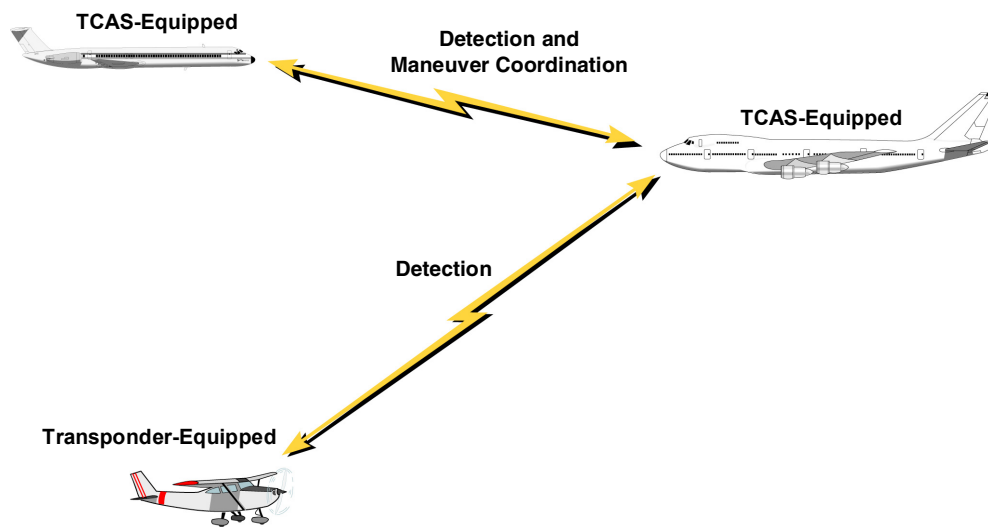


Figure 1-5: TCAS Coordination Levels

The TCAS pilot interface includes two cockpit displays – the traffic display and the RA display. These two displays may either be separate or incorporated into one single unit. Figure 1-6 shows an example traffic display and RA display incorporated into one unit. The information shown by the traffic display includes the position, vertical speed and altitude of other aircraft relative to its own aircraft, with increasing threat levels depicted by different symbol colors and shapes. The RA display provides the pilot with the appropriate resolution maneuver by displaying either the vertical rate or pitch angle to fly or avoid. The RA display shown in Figure 1-6 is implemented in a vertical speed indicator (VSI). The RA shown in Figure 1-6 is a “climb” RA at a vertical rate of 1500 to 2000 ft/min.

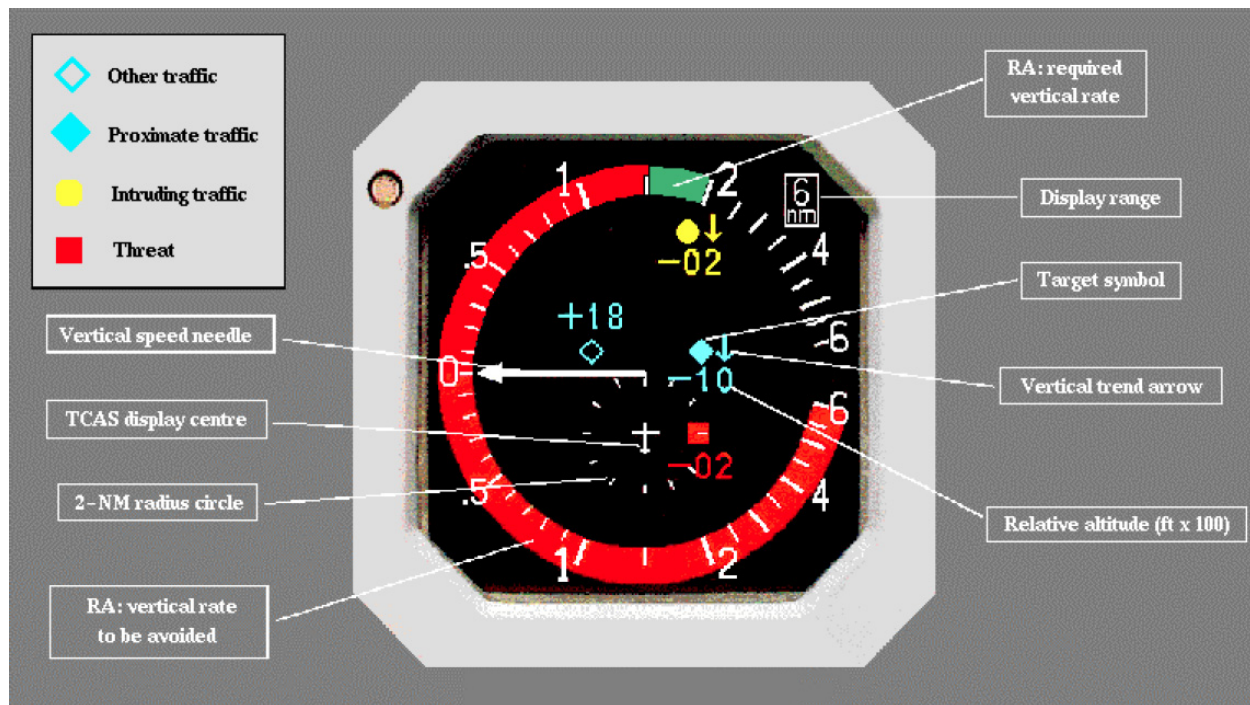


Figure 1-6: TCAS Display [6]

As the safety benefits of installing TCAS became evident, several countries participating in the International Civil Aviation Organization (ICAO) began to mandate the carriage of TCAS on aircraft exceeding a certain weight or passenger capacity. The United States was the first member of ICAO to require TCAS in 1993, followed by all European countries, Argentina, Australia, Chile, Egypt, India, and Japan. Following a midair collision between a Saudi Boeing 747 and a Kazakhstan Ilyushin 76 in 1996, ICAO proposed worldwide mandatory ACAS II (RA-capable) carriage on all aircraft above certain weight or passenger seat limits, beginning in 2003. Starting on 1 January 2005, a worldwide ICAO requirement for ACAS II equipment was mandated for all aircraft with more than 19 passenger seats or with a maximum takeoff weight of more than 5,700 kg.

1.3.2. TCAS on UAVs

Because it has already been developed and is currently operational, TCAS presents a potential near-term safety benefit for Global Hawk. The U.S. Air Force ACC established a requirement to equip RQ-4 aircraft with TCAS in order to increase the safety of operations to comply with FAA Order 7610.4. Because Global Hawk's operator is able to control vertical velocity, it would be possible to provide TCAS traffic and RA displays to the operator and allow

him to conduct traffic avoidance maneuvers to comply with TCAS RAs. The question, then, is whether such operation would be safe.

Several concerns exist in equipping UAVs with TCAS. UAVs were not originally considered when the various TCAS and ACAS mandates were drafted by ICAO. Although Global Hawk is above the weight requirements for ACAS II equipage, TCAS on UAVs was not intended to be part of the ICAO mandate. The safety studies that were conducted to certify TCAS all assumed that the aircraft would have a pilot onboard, and therefore TCAS would provide a benefit in terms of increasing situational awareness and assisting in the visual search for air traffic. Since UAVs do not have a pilot onboard to look outside the aircraft, situational awareness does not apply in the same way as manned aircraft. Due to the bearing error and update rate of TCAS, the FAA and ICAO have stated that the TCAS display alone is not sufficient to provide the operator with enough situational awareness to avoid the threat. The inability to perform visual acquisition means that the traffic display information cannot be corroborated by the UAV operator, and therefore the certification authorities are concerned about its use.

In addition, because TCAS operates by interrogating transponders on equipped aircraft, non-cooperative traffic, or aircraft without transponders, are not tracked by TCAS. Aircraft are only required to be equipped with altitude-reporting transponders in Class A, B, and C airspace, and Class E airspace above 10,000 feet. In the low-altitude Class E and uncontrolled airspace through which UAVs may fly, TCAS would be unable to detect unequipped intruders, and there is currently no capability for a UAV pilot to visually acquire these types of threats.

From prior simulation analysis, it is also known that slow pilot responses to resolution advisories can increase the risk of collision to greater than what it would be without TCAS. Because of the BLOS nature of Global Hawk's control strategy at long ranges, a certain amount of communication latency may exist between the aircraft and the pilot on the ground. This may cause delayed responses to RAs if the pilot were to command the aircraft to execute avoidance maneuvers, and safety could possibly be degraded.

Rather than equipping UAVs with a TCAS II system capable of generating RAs, an additional option under consideration would be to equip UAVs with TCAS in TA-only mode, which would alert the pilot on the ground of an intruder aircraft but not provide a collision avoidance maneuver recommendation. Figure 1-7 shows a prototype TCAS traffic display for

Global Hawk, based on this concept. Equipping UAVs with TCAS in TA-only mode is under debate since pilots are not authorized to respond to TAs alone, and there is no capability to visually acquire the threat.



Figure 1-7: Prototype Global Hawk TCAS Display [4]

Another option would be to allow TCAS to take control of the UAV and automatically execute the avoidance maneuver. This level of automation would effectively take the UAV pilot out of the collision avoidance process. Numerous studies have shown that the level of safety provided by TCAS increases with the accuracy and consistency of RA responses. Safety would be improved with an immediate and correct TCAS response each time an RA is issued, if there are no system failures and all the information is perfectly accurate and complete. However, TCAS has not yet been integrated with an autopilot system and is not certified for automatic maneuver response.

Recently, more consideration has taken place as to the steps needed to evaluate the performance of TCAS on UAVs, serving as a topic of discussion at recent ICAO Surveillance and Conflict Resolution Systems Panel (SCRSP) meetings. The original development of TCAS required extensive tests, analyses, computer simulations and operational evaluations, at a cost of approximately \$400 million in FY2001 dollars [7]. Such development has not occurred for UAVs, and it is clear that a rigorous effort is needed to determine the necessary requirements and procedures for operation of TCAS on UAVs. Until this is accomplished, the safest way to operate UAVs in the NAS, as recommended by ICAO, is to equip them with a 25-foot

altitude-reporting Mode S transponder. The Global Hawk program office has responded to the requirement for additional research and testing by funding ICAO-recommended TCAS safety studies for Global Hawk. In addition, flight tests are planned for late 2006 which will evaluate the performance of TCAS onboard Global Hawk.

2. Collision Avoidance Safety Analysis

2.1. Safety Analysis Approach

Historically, the process of conducting a collision avoidance safety analysis for a manned aircraft has included three complementary techniques. The first technique is a static analysis that uses a “fault tree” which identifies and analyzes failures in the entire collision avoidance operating environment. The second method is to use dynamic simulation to evaluate TCAS performance computationally. The third main technique is analysis of TCAS performance on an aircraft accomplished through flight testing. The combination of these three techniques allows safety to be quantified and a collision avoidance system to be thoroughly evaluated. Safety analysis can be conducted in a similar manner for UAVs.

An event tree, or fault tree, provides both a quantitative and qualitative means to identify and analyze failure modes in the end-to-end collision avoidance process. All possible means by which a collision could occur are identified and organized into a logical structure. These failure modes are not limited to TCAS alone. They may include air traffic control, radio, navigation or communication system failures, pilot errors, or aircraft flight control system failures. After the fault tree is generated, each process leading to failure can be studied and the root causes and interactions identified. System failures can have a significant impact on risk, and so this is an important area of study.

The dynamic simulation technique involves robust computational simulation of aircraft encounters and subsequent statistical analysis of the results. The development of TCAS for piloted aircraft included millions of computer simulations to quantify the protection provided by TCAS in a wide range of traffic encounters. Safety studies were performed using updated TCAS algorithms, to estimate how TCAS could further reduce the risk of mid-air collisions. This method assumes that TCAS works properly. For the purposes of simulation, this means TCAS receives accurate information, such as range, bearing and altimetry information from the intruder aircraft, and there are no power supply failures or general faults. The simulation requires an air traffic model, as well as models for pilot and aircraft response and the TCAS logic. The purpose of dynamic simulation is to predict TCAS performance over the entire expected life of the

system. In other words, a wide range of possible scenarios in which a TCAS-equipped aircraft may encounter another aircraft are considered.

The third technique includes operational evaluations that may be conducted which test TCAS performance in flight. Information acquired from the flight tests may be fed back into the fault tree or dynamic simulation. The TCAS logic has occasionally been updated based on results from these evaluations.

For this thesis, a dynamic simulation was developed and executed to evaluate TCAS performance on Global Hawk. In prior TCAS studies, ground-based radar data were collected and examined to find encounters between two aircraft where TCAS would alert the pilots of a potential mid-air collision [8]. Structured airspace encounter models, or traffic models, were then developed which reflected the statistical characteristics of the airspace in which these radar data were collected. Millions of encounters between two aircraft were then generated based on this statistical model and simulated using the TCAS logic implemented in computational tools. For the Global Hawk study, existing airspace encounter models were modified to reflect Global Hawk's flight characteristics. Encounter models are discussed in further detail in Section 2.1.3.

2.1.1. *Dynamic Simulation*

A Monte Carlo simulation was used to evaluate the effectiveness of TCAS in lowering the risk of a near mid-air collision (NMAC). NMACs are defined as encounters where the vertical miss distance (VMD) is 100 feet or less and the horizontal miss distance (HMD) is 500 feet or less. In general, during the simulation a climbing or descending maneuver may be performed by one or both aircraft in response to TCAS advisories to change the VMD of the aircraft at the closest point of approach (CPA).

The effect of TCAS on collision risk is expressed through the "risk ratio," which is defined as the probability of an NMAC with TCAS divided by the probability of an NMAC without TCAS. Although TCAS cannot entirely eliminate the collision risk, it can reduce the probability of an NMAC to less than what it would have been without TCAS. A risk ratio of less than one indicates that TCAS is effective in improving safety by lowering the risk of a collision.

Figure 2-1 graphically shows how risk ratio is computed. The left graph in Figure 2-1 schematically indicates the probability of an NMAC without TCAS, p , based on a large number of Monte Carlo simulations. The right graph indicates the probability of an NMAC with TCAS

when run over the same set of encounters. In this example, 90% of the pre-existing collision risk is resolved by TCAS, but two components of risk remain: unresolved risk and induced risk. Unresolved risk represents those encounters where TCAS fails to remove a pre-existing risk, and induced risk is the potential for TCAS to cause a collision that did not exist in its absence.

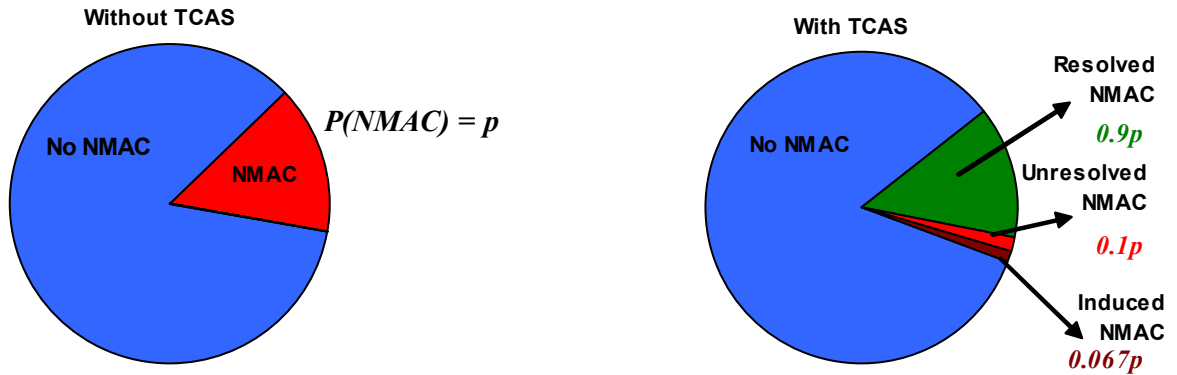


Figure 2-1: Risk Ratio

Equation 2-1 shows how the unresolved and induced components of risk ratio are calculated. The total risk ratio is the union of these two components. In the example from Figure 2-1, the risk ratio is $\frac{0.167p}{p}$, or 16.7%. The unresolved risk ratio component is 10%, and the induced component is 6.7%.

$$\begin{aligned} \text{Risk Ratio} &= \frac{P[\text{NMAC with TCAS}]}{P[\text{NMAC without TCAS}]} = \text{Unresolved RR} + \text{Induced RR} \\ &= \frac{P[\text{NMAC w/ TCAS, NMAC w/out TCAS}]}{P[\text{NMAC w/out TCAS}]} + \frac{P[\text{NMAC w/ TCAS, } \overline{\text{NMAC w/out TCAS}}]}{P[\text{NMAC w/out TCAS}]} \end{aligned}$$

Equation 2-1

Risk ratio is an important metric because it represents a quantitative measure of safety that can be obtained through fast-time simulation of aircraft encounters.

The Monte Carlo simulation uses each aircraft's measured altitude at CPA to compute VMD. However, the measured VMD may not be equal to the actual VMD due to altimeter error. If the distribution of combined altimeter error is known, it is possible to compute the probability of an actual VMD less than 100 ft, which would result in an NMAC during the encounter.

Assuming a Laplacian probability distribution function as specified by the ICAO standards, the altimeter error, e , for one aircraft is distributed according to Equation 2-2:

$$p(e) = \frac{1}{2\lambda} \exp\left(\frac{-|e|}{\lambda}\right) \quad \text{Equation 2-2 [9]}$$

where λ is a statistical parameter based on altitude. The probability of an NMAC for a single encounter can then be obtained by integrating the combined altimeter error distribution (using the convolution of two of the distributions given in Equation 2-2) of the two aircraft over the range of errors that would result in a true vertical separation of less than 100 feet. Figure 2-2 shows an example combined relative altitude error distribution for a case where aircraft at 18,000 ft have a measured separation of 200 ft.

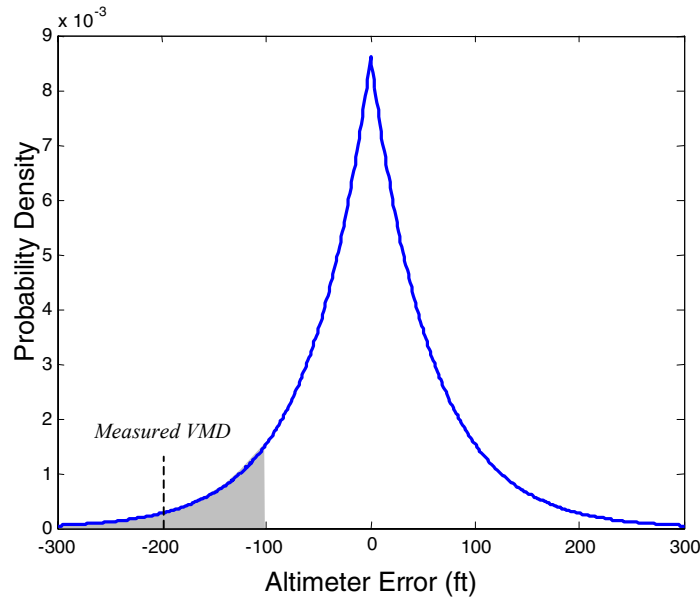


Figure 2-2: Example Relative Altitude Error Distribution (Aircraft at 18,000 ft)

If the measured VMD for a particular encounter without TCAS were 200 ft, the NMAC probability for that encounter would be determined by integrating the distribution from 100 to 300 ft, since any altimeter error in this range would result in a true vertical separation of less than 100 ft. The result is an NMAC probability of approximately 0.24. If one or both aircraft maneuvered in response to TCAS and the measured VMD for this encounter increased to 300 ft, the probability of an NMAC would be found by integrating altimeter error between 200 ft and 400 ft, which gives 0.054. Risk ratio for that particular encounter would then be $0.054/0.24 =$

0.22. Each encounter run k yields a $P_0(k)$ (without TCAS) and $P_1(k)$ (with TCAS), where P_0 and P_1 are the probabilities of an NMAC for the run. Then,

$$RR = \frac{\sum_{i=1}^N \frac{1}{N} P_1(i)}{\sum_{i=1}^N \frac{1}{N} P_0(i)} \quad \text{Equation 2-3}$$

In this way, the risk ratio can be computed for a set of thousands of encounters using the mean probabilities of NMAC with and without TCAS.

2.1.2. Simulation Overview

To obtain the necessary results for calculating risk ratio, a simulation tool is required that focuses on dynamic interactions between several components of the collision avoidance process. The simulation tool used for this thesis focuses on interactions between TCAS, pilot response, and aircraft response during a close encounter between two aircraft that occurs in a 50- to 60-second window near the CPA.

Figure 2-3 shows a schematic of the simulation process. Each scenario involves two aircraft already in a close encounter. No other considerations of events leading up to the encounter are included in the simulation process, such as procedures, pilot error or loss of separation by ATC.

The simulation process begins by generating an encounter that specifies each aircraft's initial conditions and planned trajectory. Once the initial conditions for an encounter are obtained, they are supplied to the fast-time simulation which runs two possible trajectories for each aircraft in parallel: one without TCAS (planned or scripted motion), and the other in which the aircraft responds to TCAS advisories. It is assumed that there are no effects that modify the planned trajectory other than TCAS. Pilot response and aircraft dynamics represent the aircraft motion in response to TCAS, such as a vertical acceleration in response to an RA, and may include some amount of delay in pilot reaction. The simulated motion of each aircraft is updated each time step and in turn affects how the TCAS logic behaves in the next time step. After the simulation is completed, VMD with and without TCAS are recorded and converted into $P[NMAC]$ for each run. Finally, risk ratio is computed by dividing the mean $P[NMAC]$ with

TCAS] by the mean $P[NMAC \text{ w/out } TCAS]$ over a set of several thousand encounters, as described in Section 2.1.

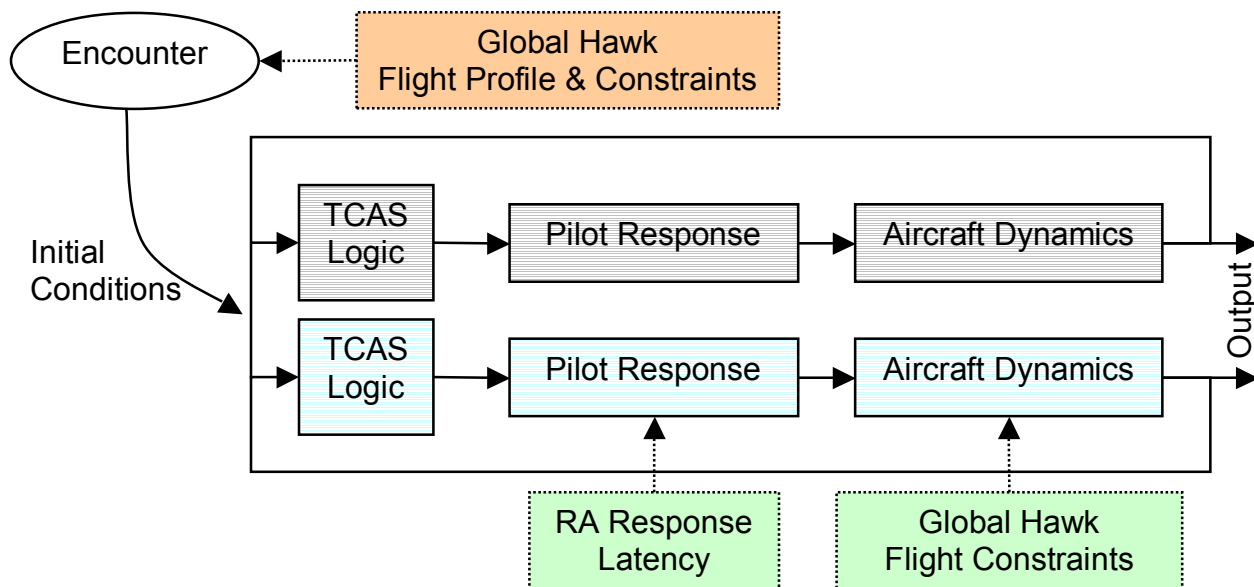


Figure 2-3: Simulation Schematic

In order to evaluate TCAS effectiveness on Global Hawk, one aircraft in each simulated pair of aircraft in the encounter is replaced with Global Hawk. This in turn causes changes as indicated by the dashed boxes in Figure 2-3.

First, Global Hawk’s mission profile and aircraft design cause several of its flight characteristics to be different than a conventional aircraft, and affect its planned trajectory during an encounter with another aircraft. Several parameters governing the encounter geometry for one of the two aircraft (i.e. vertical maneuver, airspeed, and bank angle), were modified to reflect Global Hawk’s flight profile and constraints.

Second, specific dynamic interactions between Global Hawk and another aircraft are affected by Global Hawk’s TCAS RA response. Global Hawk’s climb rate and vertical acceleration limits affected the “Aircraft Dynamics” block, and varying amounts of RA response delay were simulated as part of the “Pilot Response” block. RA delay is the amount of time that passes between when an RA is issued and when the aircraft begins responding to it. Because the actual communication latency for Global Hawk is unknown, a parametric study was conducted to determine how much delay is acceptable before TCAS fails to improve safety.

The software used for simulation in this thesis was developed in the Matlab computing environment and has three components: a graphical user interface (GUI) used to define the initial conditions of the simulation, an encounter generator that uses the conditions specified in the GUI to generate millions of encounter scenarios, and a dynamic simulation developed in Simulink that uses Honeywell TCAS software to simulate aircraft responses during each scenario [10]. A six degree of freedom point mass dynamic model is used to simulate aircraft motion. Models are included for range, bearing, and altitude error as well as pilot response.

Post-processing of the results includes the calculation of $P[NMAC]$ with and without TCAS for each run, the average value over a set of runs, and the calculation of risk ratio for each set of runs, as described previously.

Shown in Figure 2-4 is an example output of a single simulation run. In the example, the two aircraft trajectories are shown in the top three graphs, one in black and the other in blue. A top-down plan view is shown in the first graph, and two side views are shown in the second and third graphs, one with the two aircraft approaching each other and the other with the two aircraft trajectories vs. time. CPA occurs at $t = 40$ seconds. The dashed black line represents the aircraft's planned trajectory, while the solid line represents its response to a TCAS RA. In this example, only the black aircraft changes its planned trajectory in response to TCAS. In the bottom three graphs, range, vertical acceleration and vertical speed are shown for each aircraft throughout the scenario. The required vertical rates from TCAS RAs are shown by the gray and light blue shaded areas in the last graph. In this example encounter, the two aircraft approach each other at a fairly small closure angle and shallow vertical rates. At $t = 13.5$ sec, the blue aircraft receives a "Do Not Climb" RA from TCAS, and at $t = 15$ sec, the black aircraft receives a "Climb" RA. Both aircraft respond to the RAs five seconds after they are issued, and a "Do Not Descend" RA is issued to the black aircraft at $t = 25$ sec. The aircraft responses cause the VMD for the example encounter to increase from 560 feet to 788 feet.

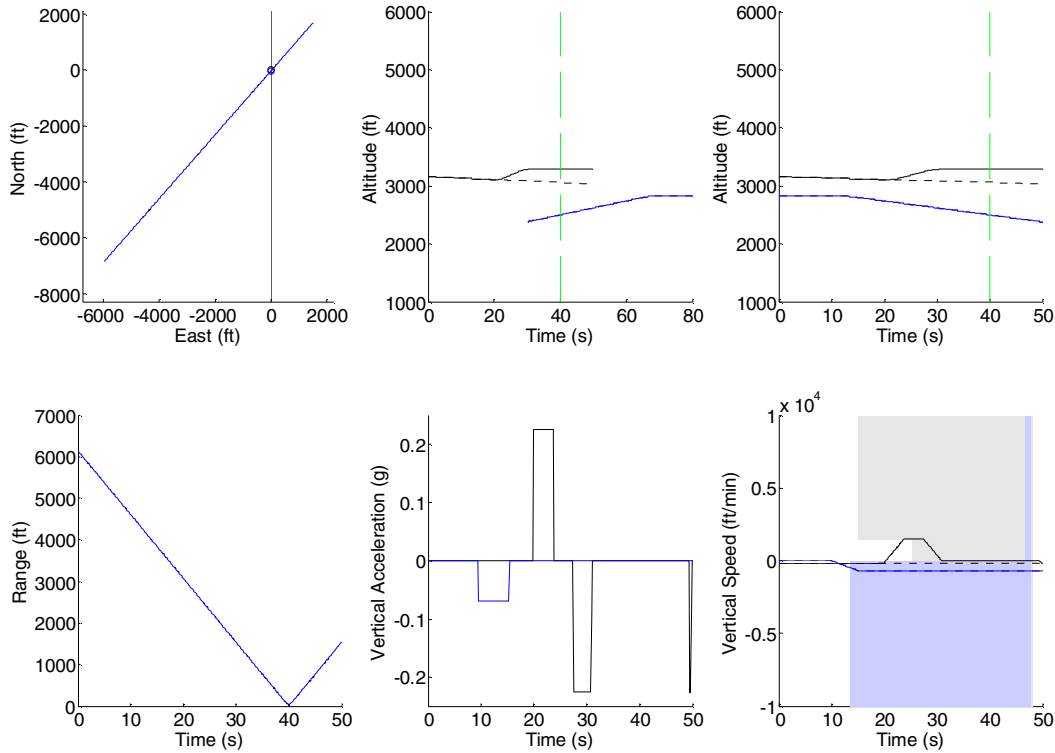


Figure 2-4: Example Scenario Output

2.1.3. Encounter Generation

To reflect the types of two-aircraft encounters that actually happen during flight within a given airspace, a viable simulation requires an airspace encounter model built from thousands of hours of radar data. The model is based on such parameters as altitude, airspeeds, or maneuvers performed by one or both aircraft in close encounters. Observed frequencies of events from the radar data are then tabulated in probability tables. By selecting new parameter values based on the tabulated statistics from the radar data, millions of encounters can then be generated and simulated that reflect actual situations.

Each encounter focuses on two aircraft (treated as point masses) in a 50- to 60-second window around the CPA. Depending on the specific encounter parameters, vertical (climb or descend) or horizontal (turning) maneuvers may be planned by one or both aircraft, in the absence of TCAS, during the encounter.

Two previously developed encounter models were used for this thesis. One was defined by the International Civil Aviation Organization (ICAO) and the other was developed during the 2000 European Airborne Collision Alerting System Analysis (ACASA) study [9, 11]. These

encounter models and the process discussed in this section have been widely used and accepted by the FAA and ICAO. The following discussion of each parameter will focus on the European model. The ICAO model uses a somewhat similar process to generate encounters [9].

Figure 2-5 shows the parameter dependency for the European model. The first parameter to be selected is the altitude layer in which to generate encounters. The ICAO encounter model is separated into six altitude layers and the European model contains five. All other parameters for an encounter are based on the altitude layer.

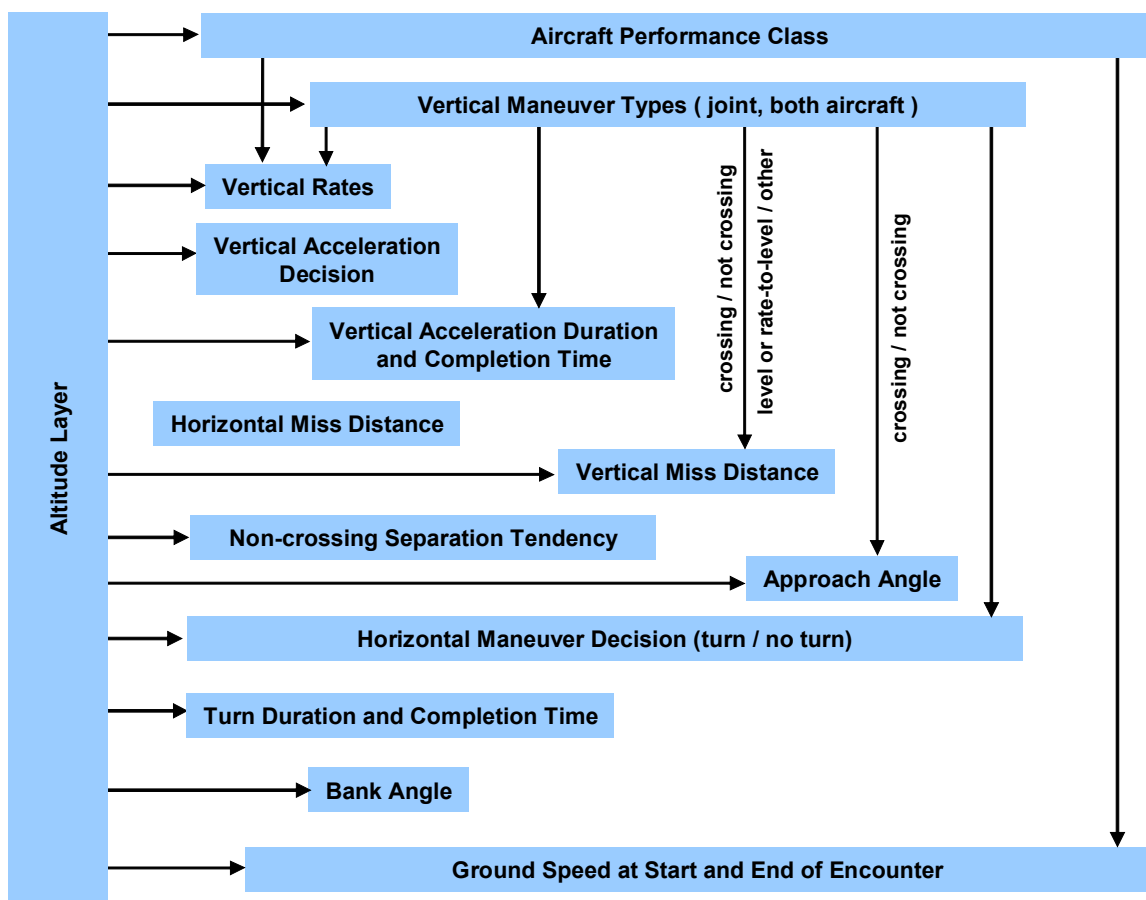


Figure 2-5: Encounter Model Parameter Dependency

The altitude layer limits are shown in Figure 2-6, along with the probability that a generated encounter lies within each layer. Thousands of encounters are generated within each altitude layer and divided according to their respective weights in order to reflect the probabilities of aircraft encounters throughout the entire airspace.

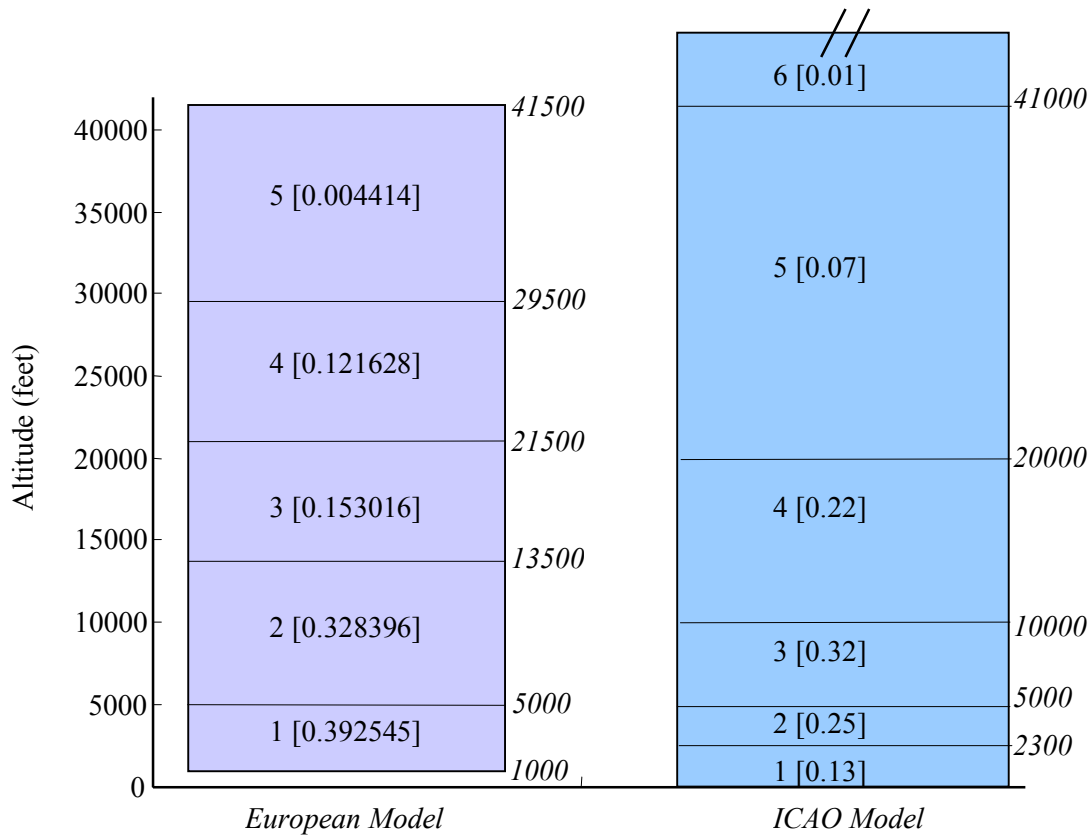


Figure 2-6: Encounter Model Altitude Layers (Probabilities in Brackets)

Based on the altitude layer, two aircraft are selected from a performance class table which determines aircraft performance characteristics such as vertical rate limits, maximum and minimum airspeeds, and ceiling.

A planned vertical maneuver type is then selected for each aircraft. Vertical maneuvers are based on initial and final vertical rates, and are categorized into nine classes. Figure 2-7 shows the nine possible vertical maneuvers for the European traffic model based on beginning and ending vertical profile (climb, level, or descend).

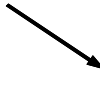
End Begin	Level	Descent	Climb
Level			
Descent			
Climb			

Figure 2-7: European Encounter Model Vertical Maneuver Classes

As an example, a level-climb profile would represent an aircraft initially at a level flight condition and starting a climbing maneuver. To provide some variety in the vertical profile of the encounter mixture, a level segment can include any vertical rate between ± 400 ft/min. Selection of a vertical maneuver also includes the consideration of whether the two aircraft will have flight paths whose altitudes cross each other during the encounter, termed “cruxality.”

Since each encounter involves two aircraft and there are nine maneuvers possible for each one, a total of 162 combinations of maneuvers can occur for each encounter (including crossing and non-crossing encounters). All 162 combinations are incorporated into probability tables based on flight data, from which one is selected randomly for each encounter.

Table 2-1: Vertical Maneuvers

<i>Number</i>	<i>Vertical Maneuver Type</i>
A ₁	Descent-Descent
A ₂	Descent-Level
A ₃	Descent-Climb
A ₄	Level-Descent
A ₅	Level-Level
A ₆	Level-Climb
A ₇	Climb-Descent
A ₈	Climb-Level
A ₉	Climb-Climb

$$\sum_{x=0}^1 \sum_{j=1}^9 \sum_{i=1}^9 P[A_i, A_j, x] = 1$$

Equation 2-4

As defined in Table 2-1, the nine vertical maneuver types are labeled A₁ through A₉. Equation 2-4 shows the total probability of all possible two-aircraft vertical maneuver combinations. The sum of the probabilities of all combinations, including nine vertical maneuver types for each aircraft (A_i, A_j) and the cruxality of the encounter ($x=0,1$), is equal to one. The ICAO model defines vertical maneuvers slightly differently. Rather than specifying climb, level or descend, it simply defines level and transition, which could be a climb or descend. The same general method, however, is used to select a vertical maneuver combination for the encounter.

An example excerpt from the European model vertical maneuver probability table is shown in Table 2-2.

Table 2-2: Example Vertical Maneuver Parameters, Altitude Layer 1: P[A₁,A₆,0]

<i>Cruxality</i>	<i>Starting Vertical Profile (AC1)</i>	<i>Ending Vertical Profile (AC1)</i>	<i>Starting Vertical Profile (AC2)</i>	<i>Ending Vertical Profile (AC2)</i>	<i>Probability</i>
Non-Crossing	Descent	Descent	Level	Climb	0.010432

Table 2-2 indicates about a 1% chance of selecting event $[A_1, A_6, 0]$ in altitude layer one, a non-crossing encounter where one aircraft performs a descent-descent maneuver and the other a level-climb maneuver.

Once a vertical maneuver is selected for each of the two aircraft, starting and ending vertical rates are selected from an appropriate probability table. The timing of any vertical acceleration is selected from another table to begin no sooner than five seconds into the 50-second window during which the encounter occurs.

The CPA in the European encounter model is constrained to occur 40 seconds into the 50-second simulation. VMD at CPA is uniformly selected from a window based on the vertical maneuver type, and the HMD is selected from a uniform distribution between 0 and 500 feet. Since HMD is always less than 500 feet, every encounter has the potential to be an NMAC with TCAS.

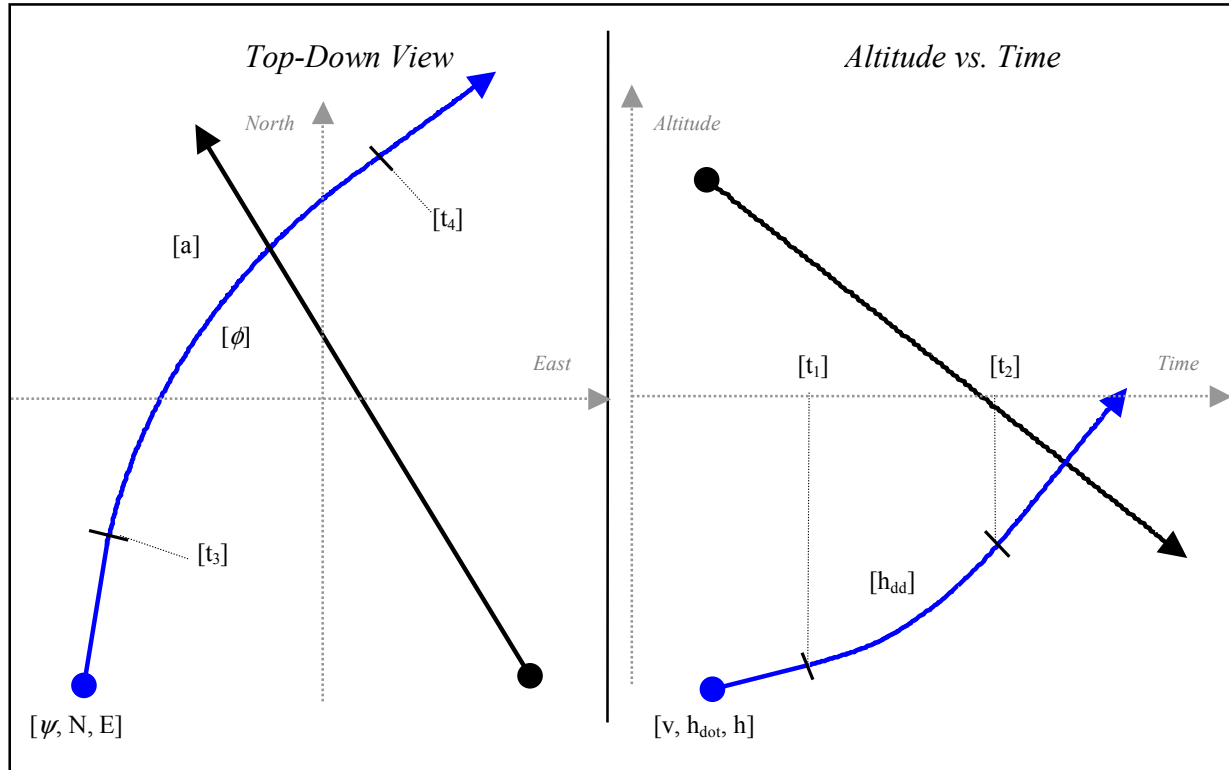
The tendency of the flight paths to diverge or converge in altitude is randomly selected, as is the lateral approach angle of the two aircraft.

Parameters governing the horizontal maneuver of the aircraft are selected next, including whether each aircraft performs a turn, its duration, and the bank angle during the turn.

Finally, beginning and ending ground speeds are selected for each aircraft.

Reverse kinematics are then used to back up the scenario from the VMD and HMD situation at CPA into the required initial conditions for each aircraft. Thirteen parameters are ultimately required for each aircraft to begin simulating each encounter scenario. These include initial true airspeed, vertical speed, heading, three-dimensional position, and several parameters that define the planned vertical- and horizontal-plane motion of the aircraft.

Figure 2-8 shows a top-down view and a plot of altitude vs. time for an example two-aircraft encounter. Each aircraft begins at its respective initial position $[E, N, h]$ with initial true airspeed $[v]$, heading angle $[\psi]$ and vertical speed $[h_{dot}]$. One aircraft performs a turn to the right in combination with a vertical acceleration, and the other continuously descends along a straight horizontal path. The aircraft whose trajectory is colored in blue performs an instantaneous bank to the angle $[\phi]$ at time $[t_3]$ to begin the turn, and comes out of the bank at time $[t_4]$, again instantaneously. Its vertical maneuver includes a vertical acceleration $[h_{dd}]$ at time $[t_1]$ to increase its climb rate. This vertical acceleration ends at time $[t_2]$.



v	Initial True Airspeed	ft/s
$h_{\dot{}}$	Initial Vertical Speed	ft/s
ψ	Initial Heading Angle	rad
N	Initial North Position	ft
E	Initial East Position	ft
h	Initial Altitude	ft
t_1	Start Time of Vertical Maneuver	sec
t_2	End Time of Vertical Maneuver	sec
h_{dd}	Vertical Acceleration during Vertical Maneuver	ft/s ²
t_3	Start Time of Turn	sec
t_4	End Time of Turn	sec
ϕ	Bank Angle during Turn	rad
a	Horizontal Acceleration	ft/s ²

Figure 2-8: Aircraft Encounter Parameters

2.2. *Global Hawk Encounter Model Modification*

As a high-altitude long-endurance aircraft, Global Hawk flies differently than a conventional aircraft. However, operational radar data are not currently available to create a specific encounter model that reflects this difference in performance. Therefore, existing encounter models were modified based on data from Global Hawk's flight manual. In order to accurately model the performance of Global Hawk during encounter simulations, several parameters from the ICAO and European air traffic models needed to be modified to reflect its flight characteristics.

Figure 2-9 shows the parameter dependencies and highlights the changes required to develop a Global Hawk-specific encounter model. The same altitude layers were used for the Global Hawk modified encounter models as for the original models. Because the proportion of Global Hawk encounters that might occur at each altitude layer is not known, the altitude layer weights were not applied to the Global Hawk encounter models. Instead, encounters were generated separately within each altitude layer and the results for each layer were compared individually against the results from the original encounter models. Of the thirteen parameters shown in Figure 2-9, six were modified to reflect Global Hawk's flight characteristics.

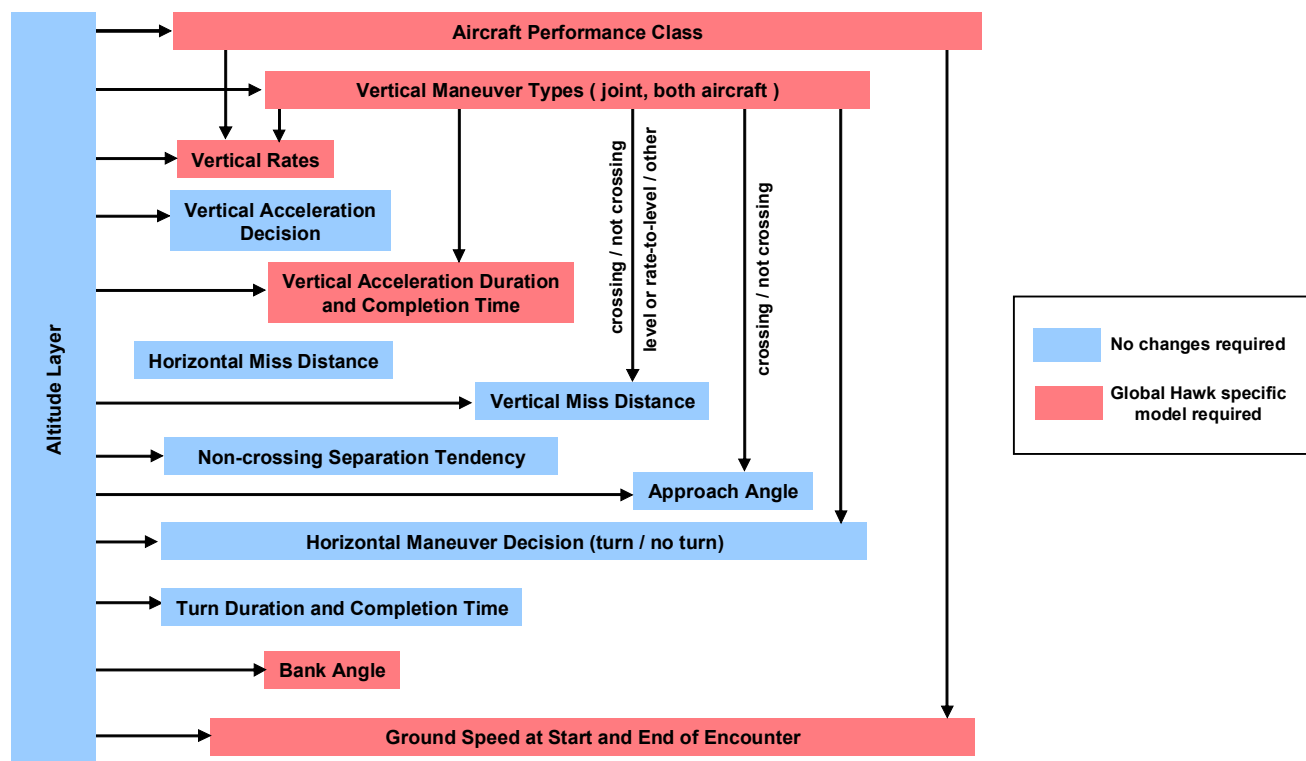


Figure 2-9: Global Hawk Encounter Model Parameter Dependency

Global Hawk's flight profile involves relatively steep climbs up to its cruising altitude, as well as steep descents to landing, slow airspeeds, and shallow turns. The parameters for one aircraft in each encounter were modified to reflect these performance constraints. In addition, the vertical maneuver mix (combinations of climb, level, and descend geometries) for Global Hawk was modified based on its higher probability of being in a climb or descent when an encounter occurs than might be the case for a conventional aircraft. These changes allowed encounters to be simulated that involved one aircraft with conventional flight parameters distributed according to the original encounter model, and one aircraft exhibiting Global Hawk's flight characteristics. The cumulative effect of these changes could then be observed by comparing the simulation results from the original encounter model (encounters between two conventional aircraft) against encounters between a conventional aircraft and Global Hawk.

Both the ICAO and European encounter models were modified to obtain two Global Hawk encounter models. The specific parameters that were changed are discussed in the following sections.

2.2.1. Airspeed

Global Hawk's airspeed limits were obtained from its flight manual [3, 12]. Figure 2-10 shows the Global Hawk airspeed envelope vs. altitude and weight, along with its limits. The red lines in Figure 2-10 show the airspeed limits selected for the Global Hawk encounter model modifications. The airspeed limits were based on maximum gross weight while climbing and minimum weight while descending, in order to capture the full range of airspeeds both during the climb to initial cruising altitude and during the descent to landing. Because the units in Figure 2-10 are given in KCAS, these speeds were converted to KTAS using the standard atmosphere.

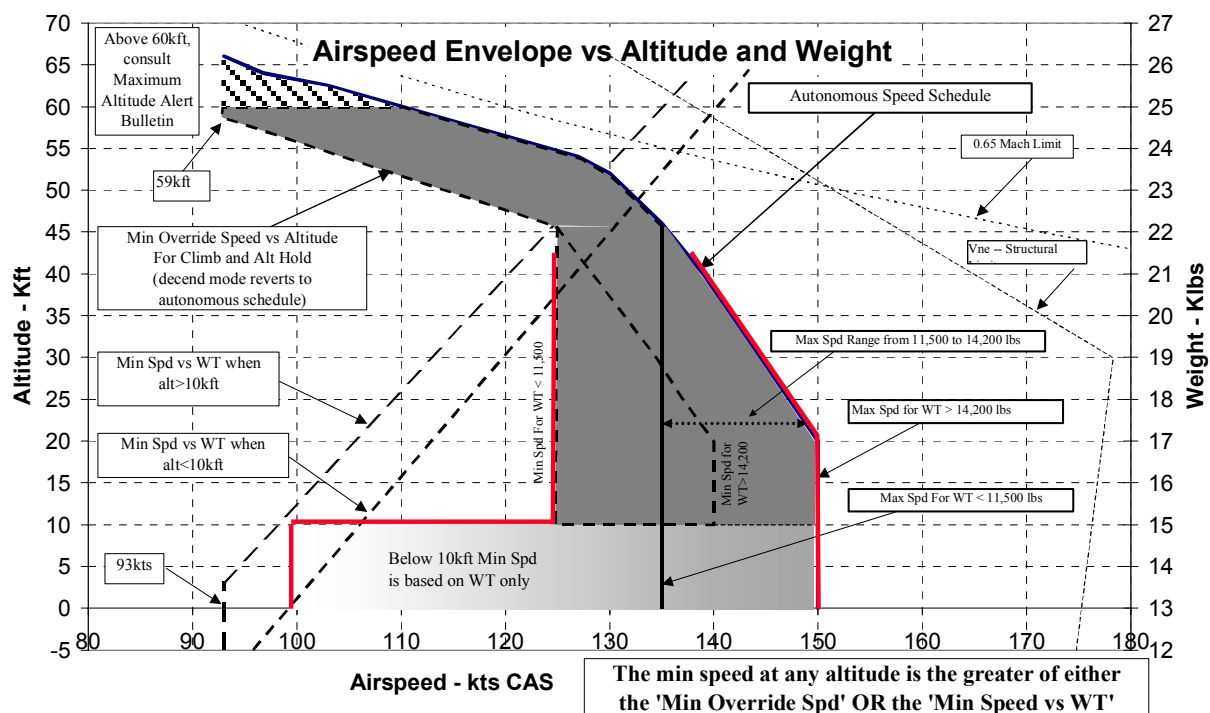


Figure 2-10: Global Hawk Airspeed Envelope [12]

Figure 2-11 shows Global Hawk's airspeed limits and its nominal climbing airspeed profile over all five altitude layers for the European encounter model. The airspeed limits shown in Figure 2-11 were added to the maximum and minimum speed tables in the original encounter models. Global Hawk airspeeds were selected according to a uniform distribution between the minimum and maximum limits.

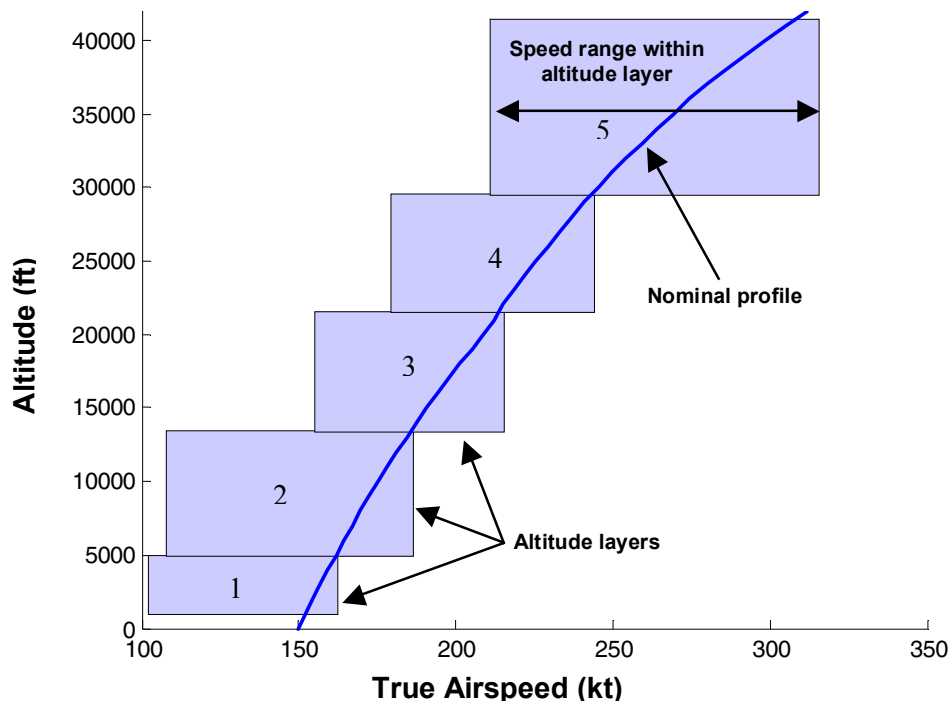


Figure 2-11: Global Hawk Airspeed Profile Based on European Encounter Model

Figure 2-12(a) shows a histogram of Global Hawk initial airspeeds in altitude layer three, while Figure 2-12(b) shows a histogram of initial airspeeds for a conventional aircraft. It is clear that Global Hawk's airspeed limitations have a large effect on the airspeed distribution of the encounters. Rather than being broadly spaced across a wide range like the conventional aircraft, the airspeeds are condensed within Global Hawk's relatively small range of allowable speeds.

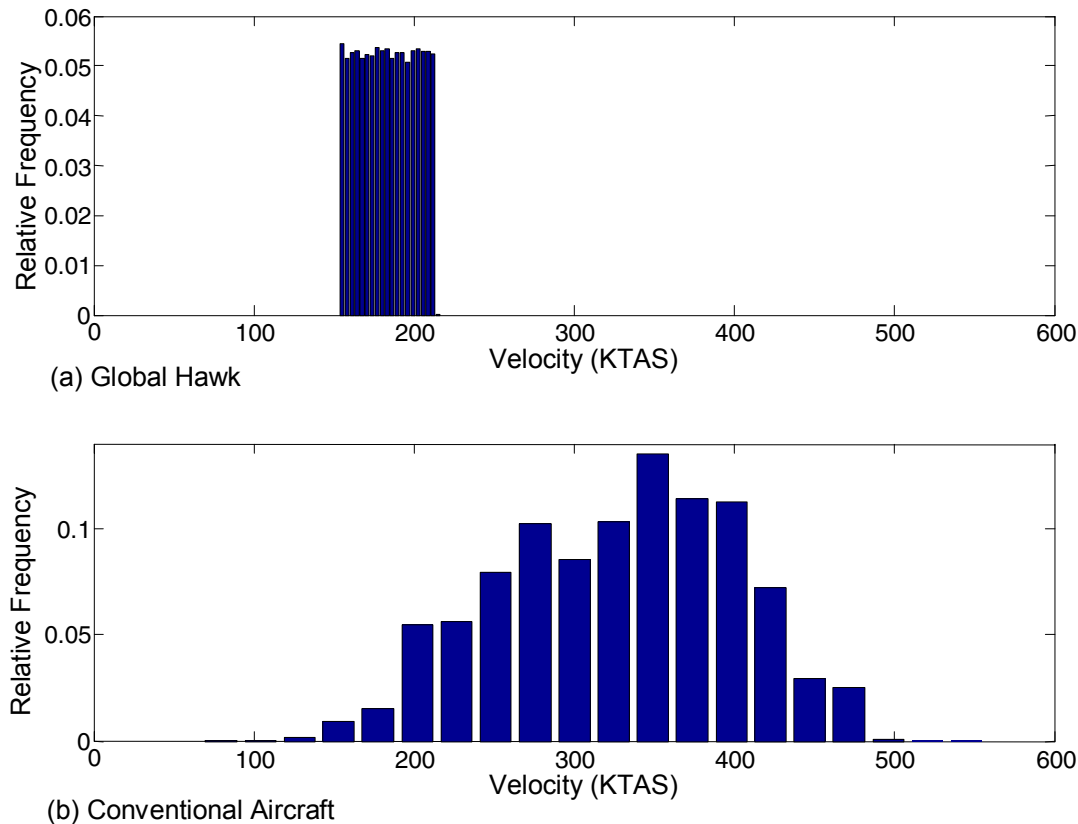


Figure 2-12: Initial Airspeed Histograms, Layer 3

2.2.2. Vertical Maneuver Probability

The Global Hawk aircraft was designed to climb steeply and quickly up to its cruising altitude. When Global Hawk encounters another aircraft, it is most likely that Global Hawk will be performing a steep climb or a descent to landing, rather than being in level cruise. The probability of Global Hawk flying a climbing or descending vertical maneuver during an encounter was therefore initially selected to be 80%. Although a specific probability is not yet available based on actual radar data, this number was selected as a reasonable estimate to develop and test the Global Hawk modified ICAO and European traffic models.

The method used to derive probabilities for each vertical maneuver type involved the definition of conditional probabilities. As discussed in Section 2.1.3, 162 possible combinations of vertical maneuvers exist for each two-aircraft encounter. Table 2-3 shows the selected probabilities of all vertical maneuver types for Global Hawk. The 0.80 probability of continuously climbing or descending was split equally into climb-climb and descent-descent

maneuvers. A 0.14 probability was assigned to level flight, and the remaining 0.06 probability was distributed equally to the other six vertical maneuvers.

Table 2-3: Example Global Hawk Vertical Maneuver Probabilities

<i>Number</i>	<i>Maneuver Type</i>	<i>Probability</i>
A ₁	Descent-Descent	0.40
A ₂	Descent-Level	0.01
A ₃	Descent-Climb	0.01
A ₄	Level-Descent	0.01
A ₅	Level-Level	0.14
A ₆	Level-Climb	0.01
A ₇	Climb-Descent	0.01
A ₈	Climb-Level	0.01
A ₉	Climb-Climb	0.40

First, the probability of each vertical maneuver type for a conventional aircraft was obtained by summing all possible combinations where one aircraft performed the maneuver. For example, the probability of a conventional aircraft following a descent-descent maneuver is:

$$P[A_1] = \sum_{x=0}^1 \left(\sum_{j=1}^9 P[A_1, A_j, x] + \sum_{i=1}^9 P[A_i, A_1, x] - P[A_1, A_1, x] \right) \quad \text{Equation 2-5}$$

where A_j represents all nine possible maneuvers for the other aircraft, for both crossing and non-crossing encounters. In altitude layer one of the European model, for example, the probability of a descent-descent maneuver by one aircraft, $P[A_1]$, is computed to be 0.23845.

Next, the conditional probabilities for each vertical maneuver were calculated. For example, the probability of a non-crossing encounter with a level-climb maneuver for one aircraft, given a descent-descent maneuver for the other aircraft, would be:

$$P[A_6 | A_1, 0] = \frac{P[A_1, A_6, 0] + P[A_6, A_1, 0]}{P[A_1]} \quad \text{Equation 2-6}$$

In layer one of the European model, the probability of a non-crossing encounter with a level-climb maneuver (A_6) for a conventional aircraft given a descent-descent maneuver (A_1) for the other aircraft is computed to be 0.04375.

Finally, using the Global Hawk probabilities defined above, new probability tables were created by multiplying the Global Hawk vertical maneuver probabilities by the conditional probabilities. For example, the probability of an encounter where a Global Hawk descent-descent meets a conventional aircraft level-climb is:

$$P[A_{1GH}, A_6, 0] = P[A_6 | A_1, 0] \cdot P[A_{1GH}] \quad \text{Equation 2-7}$$

The calculated probability for this example non-crossing encounter is 0.0175, which is almost double the value for this type of encounter from the original European encounter model.

The effect of Global Hawk's vertical maneuver probabilities on encounter generation was a higher likelihood of a Global Hawk climb-climb or descent-descent maneuver during an encounter with another aircraft. Figure 2-13 shows the probabilities for each type of vertical maneuver for the European encounter model at altitude layer three, and Figure 2-14 shows these same probabilities for the Global Hawk modified model. In the European encounter model, it can be seen that climbing and descending maneuvers are rarely selected for both aircraft. In the Global Hawk model, the Global Hawk aircraft is more likely to be climbing or descending. The highest likelihood is for a Global Hawk descent-descent maneuver (continuous descent) and the other aircraft remaining level throughout the encounter.

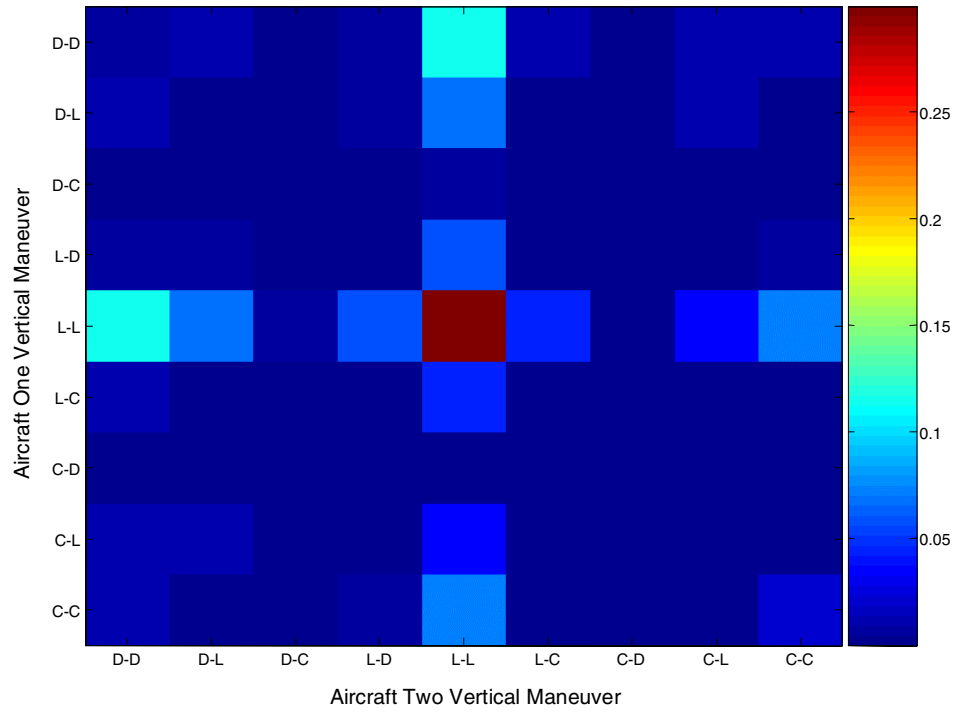


Figure 2-13: Vertical Maneuver Probabilities, European Model, Layer Three

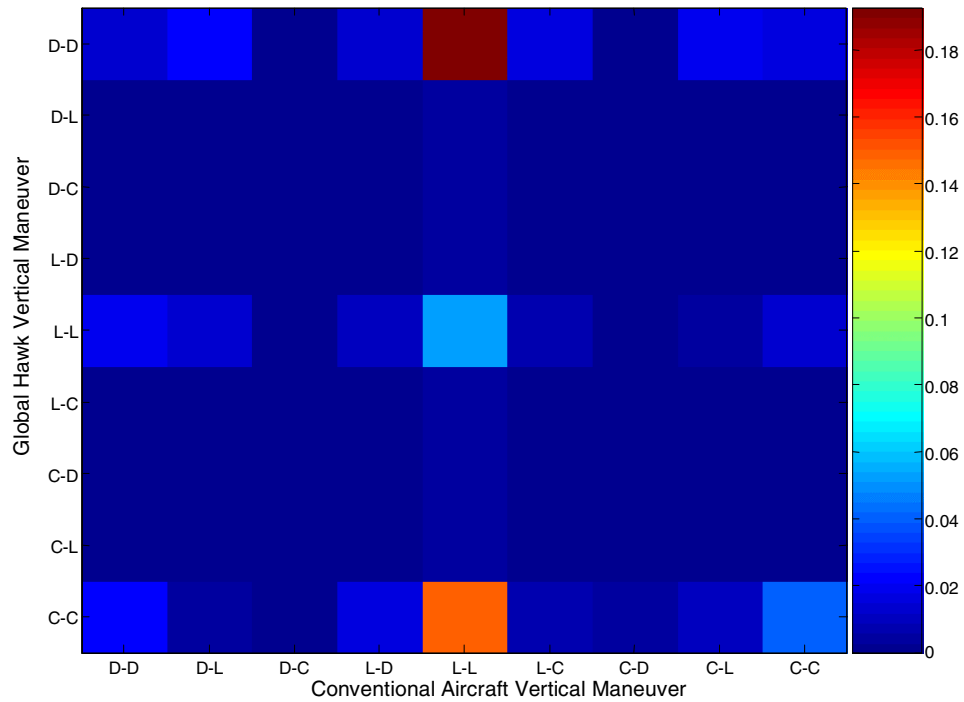


Figure 2-14: Vertical Maneuver Probabilities, Global Hawk Modified European Model, Layer Three

2.2.3. Climb Rate

Global Hawk's climbing maneuvers are generally flown at a steeper flight path angle (~ 7 deg) than that of a conventional manned aircraft (~ 4 deg). Based on the assumptions of maximum gross weight and no temperature deviation, several data points were collected from Global Hawk's climb rate chart shown in Figure 2-15.

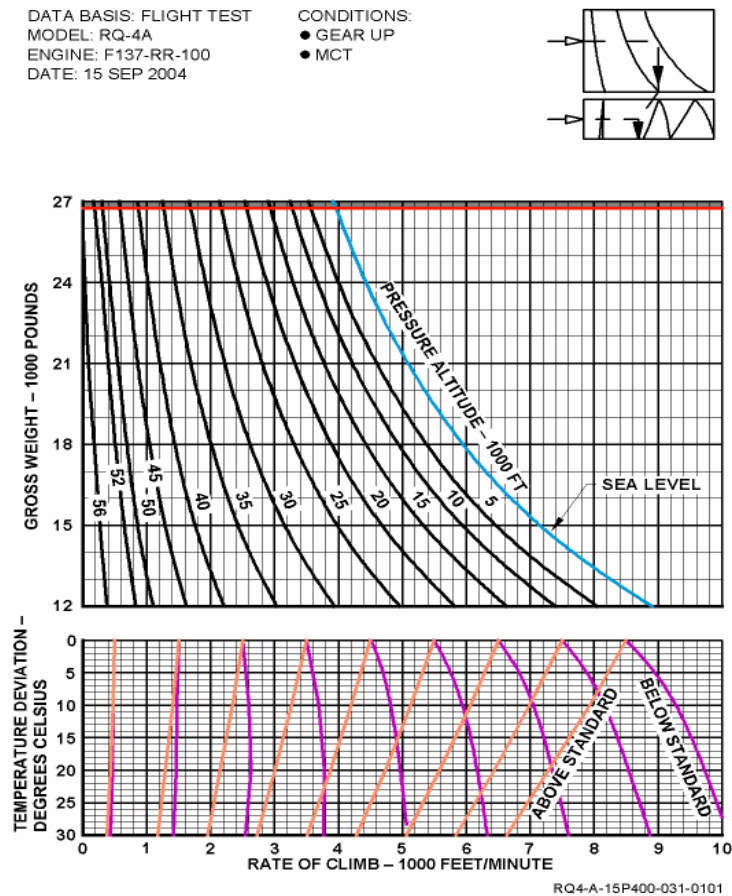


Figure 2-15: Global Hawk Climb Rate [3]

The data points were plotted against altitude, and a linear regression was performed which yielded an equation for maximum rate of climb as a function of altitude, shown in Figure 2-16.

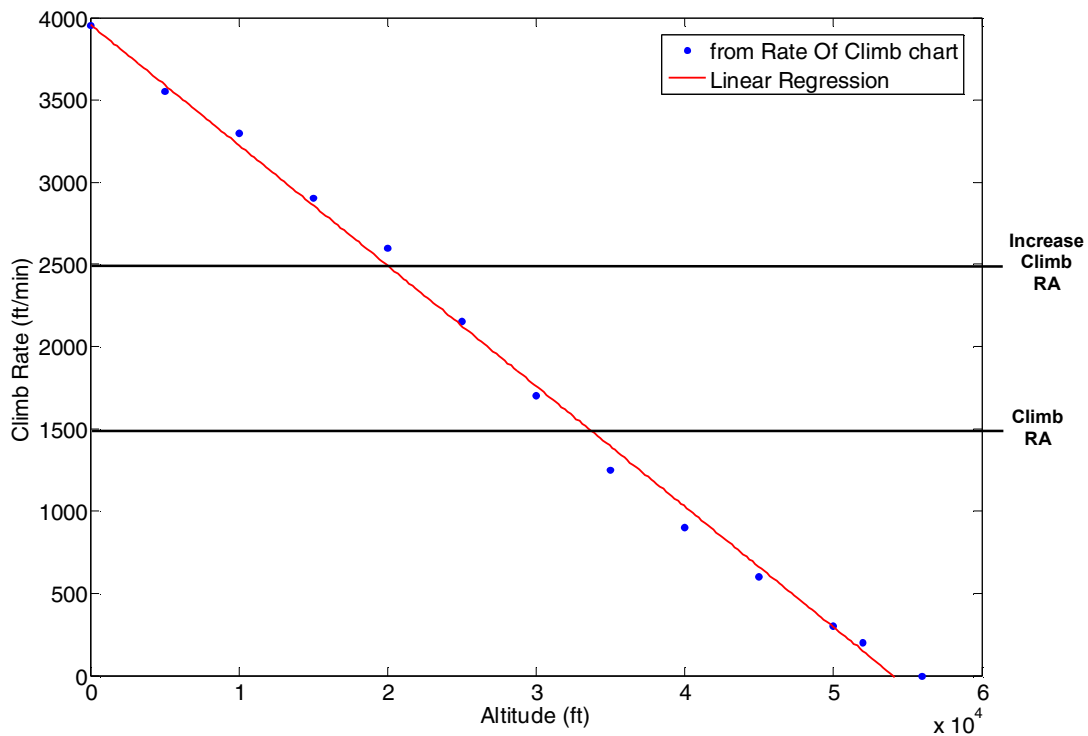


Figure 2-16: Global Hawk Climb Rate vs. Altitude, Gross Weight = 26,750 lbs

The maximum climb rate was used as a constraint both in the encounter model geometries and when simulating Global Hawk TCAS response. For Global Hawk encounter generation, the limits on climb rate were capped based on the data in Figure 2-16. The standard rate of climb for a TCAS resolution advisory is 1500 ft/min for an initial “climb” RA and 2500 ft/min for a subsequent “increase climb” RA. Figure 2-16 indicates that at altitudes greater than 20,000 feet, Global Hawk cannot exceed 2500 ft/min, and above 34,000 feet, it cannot exceed a 1500 ft/min climb rate. During the Global Hawk encounter simulation, if TCAS commanded a climb rate that was greater than what Global Hawk could perform, the actual rate of climb was constrained to the performance limit shown in Figure 2-16, based on altitude.

2.2.4. Descent Rate

Using the descent rate chart shown in Figure 2-17, the maximum Global Hawk descent rate for each altitude layer was calculated and added as a constraint to the probability tables for the ICAO and European encounter models.

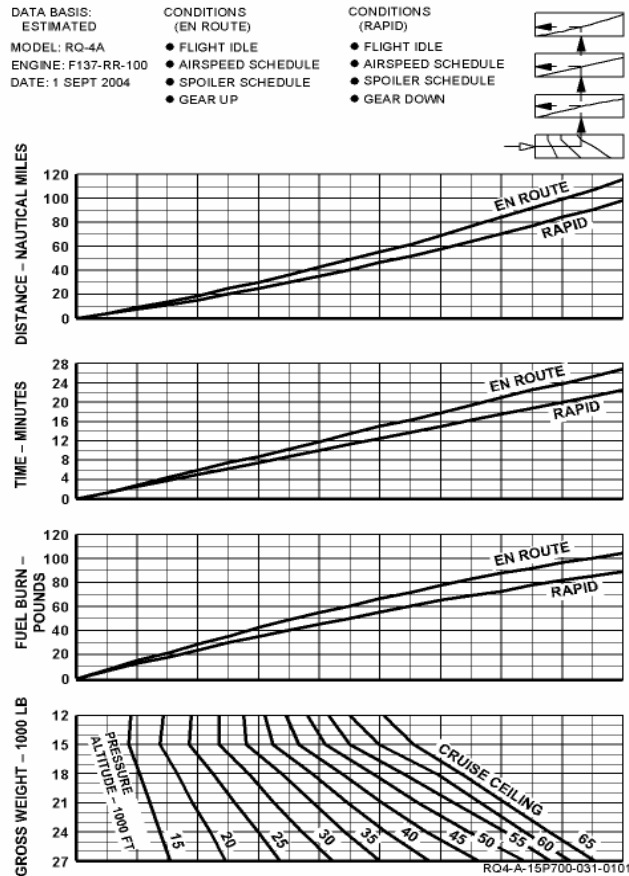


Figure 2-17: Global Hawk Descent Rate [3]

Assuming an aircraft weight of 13,000 lb and rapid descent conditions, the time to travel from the high to the low limits of each altitude layer was calculated. The total height of each layer was divided by the time to descend through that layer to give the average descent rate. The maximum Global Hawk descent rate was approximately the same for each altitude layer, 4000 ft/min. This value was implemented in the Global Hawk modified encounter models.

Figure 2-18 shows Global Hawk's initial vertical rate as randomly generated over 200,000 runs. Global Hawk's initial vertical rate does not exceed 4000 ft/min, and a large number of vertical rates are in the 1000 – 4000 ft/min range.

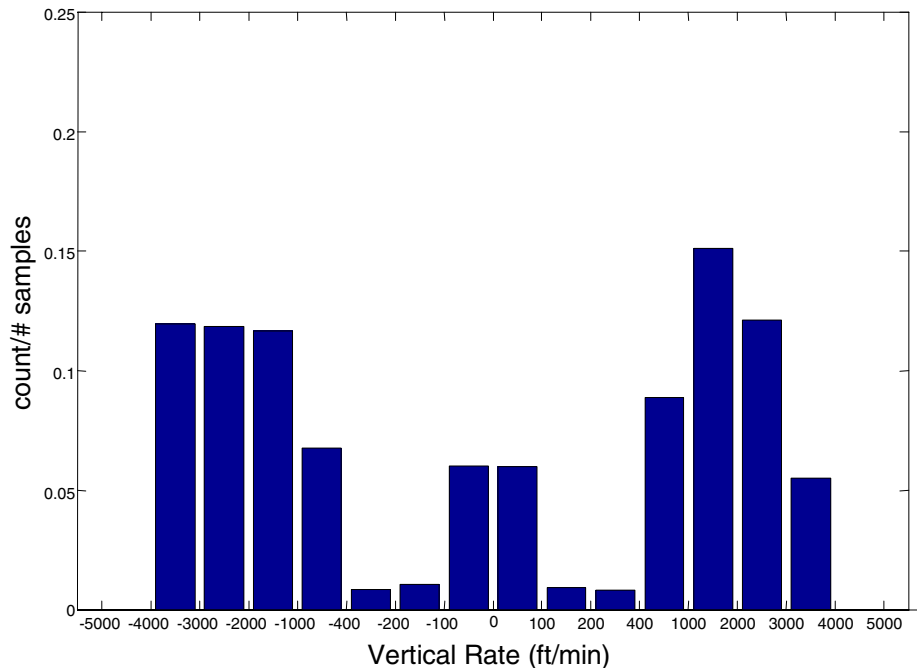


Figure 2-18: Global Hawk Initial Vertical Rate Histogram, All Altitude Layers

In contrast, Figure 2-19, generated in a similar way but for a conventional aircraft, indicates a much higher probability of an initial vertical rate of less than 100 ft/min and slightly higher vertical rate limits.

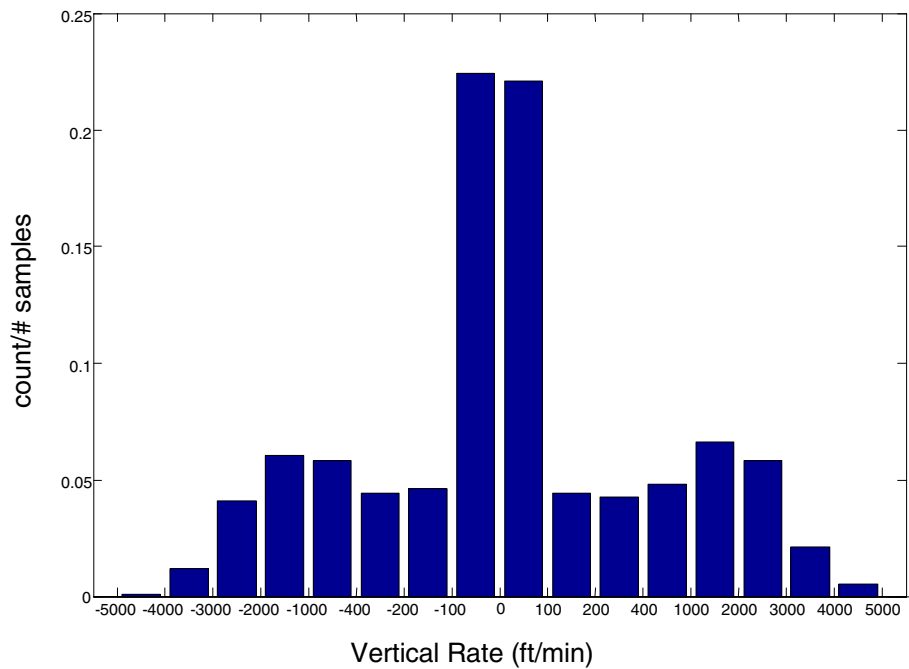


Figure 2-19: Conventional Aircraft Initial Vertical Rate Histogram, All Altitude Layers

The difference between the histograms in Figure 2-18 and Figure 2-19 arises from a combination of the Global Hawk climb and descent rate limits as well as the vertical maneuver probabilities discussed in Section 2.2.2.

2.2.5. Bank Angle

Global Hawk's bank angle schedule was used to determine limits on bank angle during maneuvering. Figure 2-20 shows Global Hawk's bank angle limits throughout its altitude envelope.

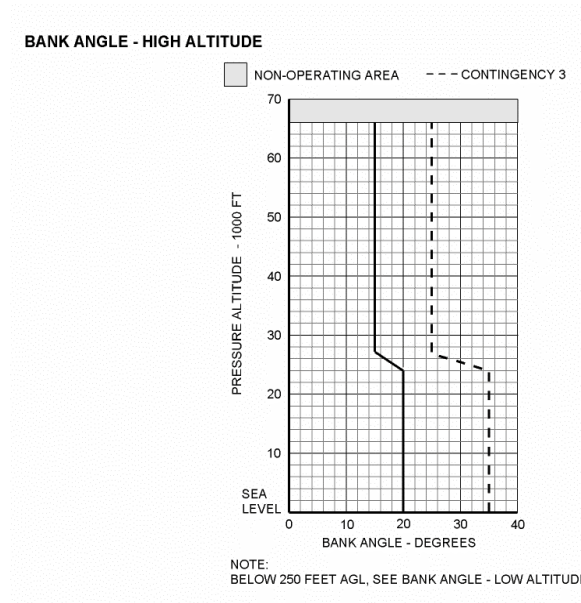


Figure 2-20: Global Hawk Bank Angle Schedule [3]

In the modified European model, the bank angle limit is 20 deg for altitude layers one through four, and 15 deg for altitude layer five. If a turning maneuver is performed during the maneuver, the bank angle randomly selected by the encounter model will not exceed these limits. This only affects the encounters where a turning maneuver is performed, and where the selected bank angle exceeds Global Hawk's limit.

2.2.6. Ceiling

Global Hawk's operating ceiling is 65,000 feet. This is higher than either of the encounter models' highest altitude. This allows encounters to be simulated at any altitude in the model, rather than capping the altitude at a lower limit as it is for other aircraft classes.

2.2.7. Vertical Acceleration

Global Hawk's pitch rate limit is two degrees per second. When TCAS issues a resolution advisory, it expects the aircraft to perform a vertical maneuver with a normal acceleration of 0.25g for an initial RA or 0.35g for an increase or reversal. Because of Global Hawk's 2 deg/sec pitch rate limit, at low speeds in certain encounters its vertical acceleration cannot meet this requirement.

Equation 2-8 shows how vertical acceleration, a , is calculated from airspeed, v , and pitch rate, $\dot{\gamma}$ (assuming a small bank angle).

$$a = v\dot{\gamma}$$

Equation 2-8

Figure 2-21 shows the pitch rate limit and its effect on vertical acceleration applied to each altitude layer.

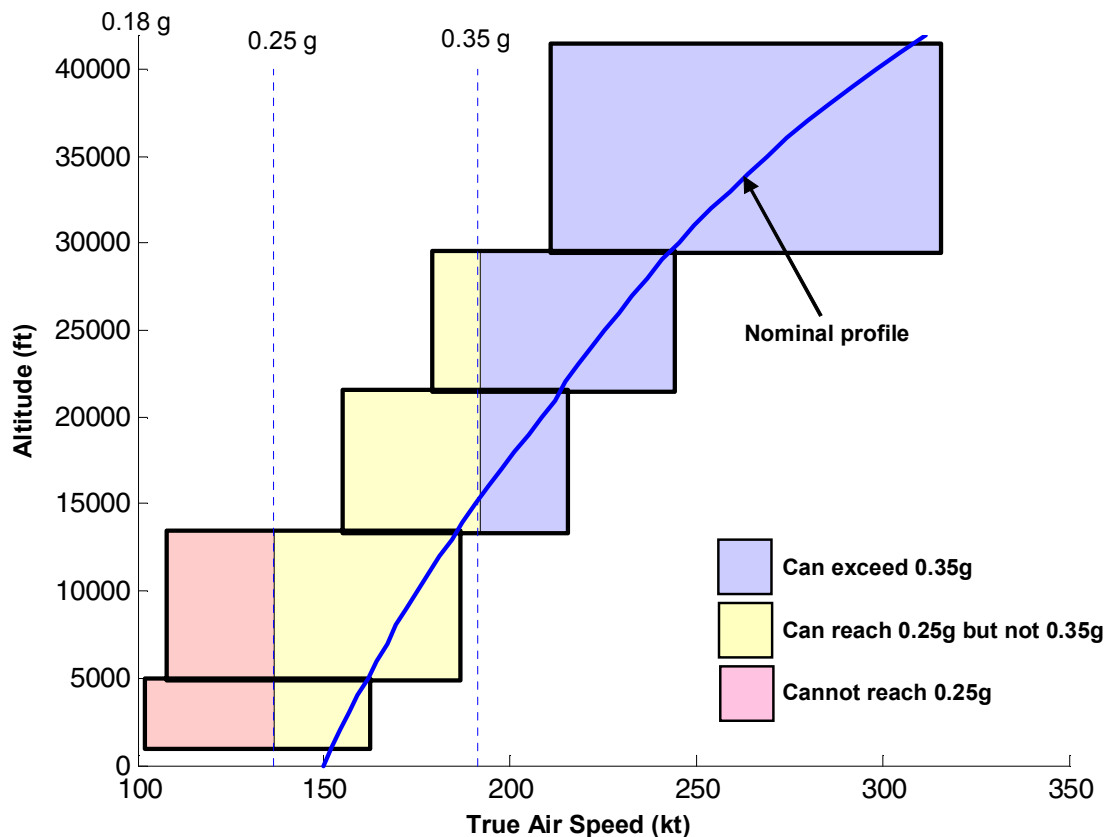


Figure 2-21: Global Hawk Vertical Acceleration Profile, European Encounter Model

Global Hawk's vertical acceleration at very slow airspeeds cannot reach the 0.25g commanded by TCAS. At other airspeeds, it can meet the 0.25g but not the 0.35g for an increase or reversal. All altitude layers except layer five are affected to some extent by this constraint. The vertical acceleration limit causes a less aggressive avoidance maneuver to be performed at lower airspeeds.

As discussed in Section 2.2.3, the target vertical rate for an initial TCAS "climb" RA is 1500 ft/min. Figure 2-22 shows simplified altitude trajectories for three aircraft performing vertical pitch-up maneuvers in response to a TCAS "climb" RA: two aircraft perform this maneuver at 0.25g (conventional) with delays of 5 and 10 seconds, and one performs the maneuver at 0.18g (Global Hawk worst case) with a delay of 5 seconds. The dashed lines in the figure represent the time at which each aircraft reaches a climb rate of 1500 ft/min. The solid red line in the figure represents a conventional aircraft trajectory response to a TCAS "climb" RA at 1500 ft/min. The aircraft pitches up at 0.25g and reaches 1500 ft/min at $t = 8.1$ sec. The total altitude gained after 30 seconds is 586 ft. The blue line demonstrates how Global Hawk's vertical acceleration limit affects its ability to meet the TCAS commanded climb rate of 1500 ft/min. Referring to Figure 2-21, 0.18g is the worst case vertical acceleration for Global Hawk, when it flies at its slowest airspeed. Because it can only meet 0.18g, it takes slightly longer to achieve the 1500 ft/min climb rate ($t = 9.3$ sec) and its total altitude gain after 30 seconds is 571 ft, slightly less than the conventional aircraft. The solid black line represents a conventional aircraft maneuvering at 0.25g but with an added delay of 5 seconds. The additional delay represents a slower pilot response to TCAS. This aircraft achieves a 1500 ft/min climb rate at $t = 13.1$ sec with a total altitude gain of only 461 ft.

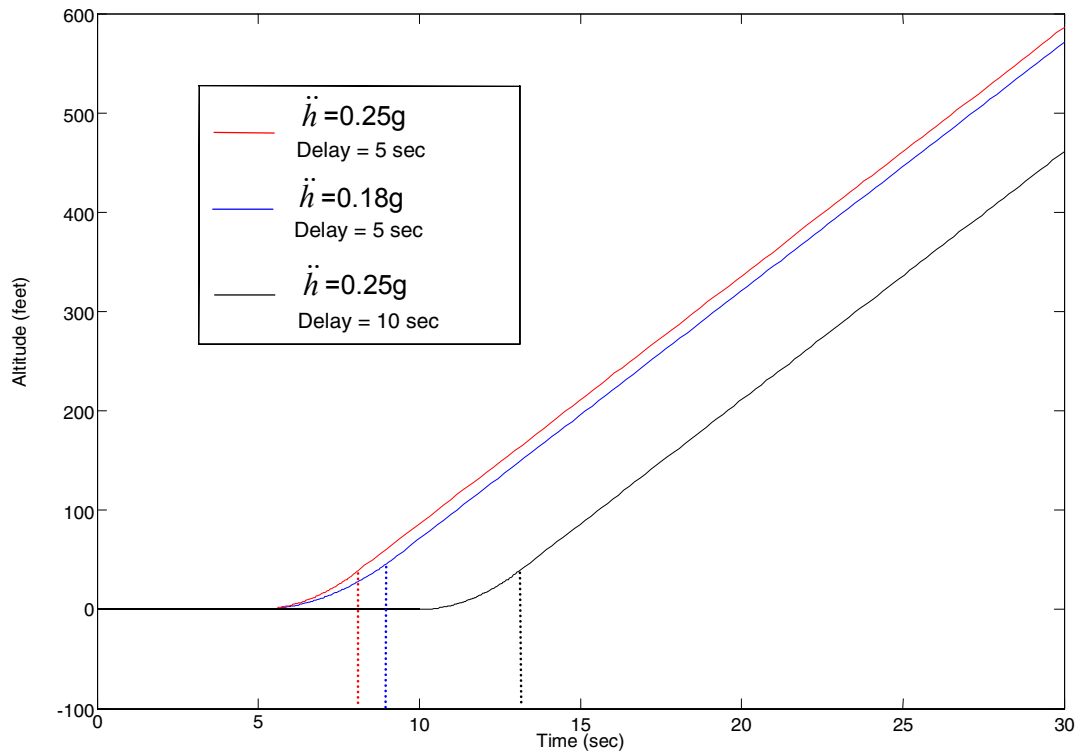


Figure 2-22: Vertical Maneuver Example

It can be seen from Figure 2-22 that a conventional aircraft performing the vertical maneuver at 0.25g but with a slight delay is comparable to performance with a lower acceleration, like the aircraft representing Global Hawk. The effect of performing the maneuver with 0.18g vertical acceleration is equivalent to performing it with an additional latency of 0.6 sec. This suggests that Global Hawk’s vertical acceleration limit has a similar effect on the risk ratio as does a slower TCAS pilot response.

2.3. Summary

Figure 2-23 highlights the changes that were needed for the simulation to reflect Global Hawk’s characteristics. Global Hawk’s flight profile, as well as some of its performance constraints, affected the way in which the geometries of the two-aircraft encounters were set up. Several of its performance constraints also affected the way Global Hawk responded to TCAS RAs during the encounter simulation. The combination of these changes allowed Global Hawk-specific encounter models to be developed, where one aircraft was conventional and the other

was specified as Global Hawk. The subsequent effect on risk ratio could then be observed after simulating thousands of these encounters.

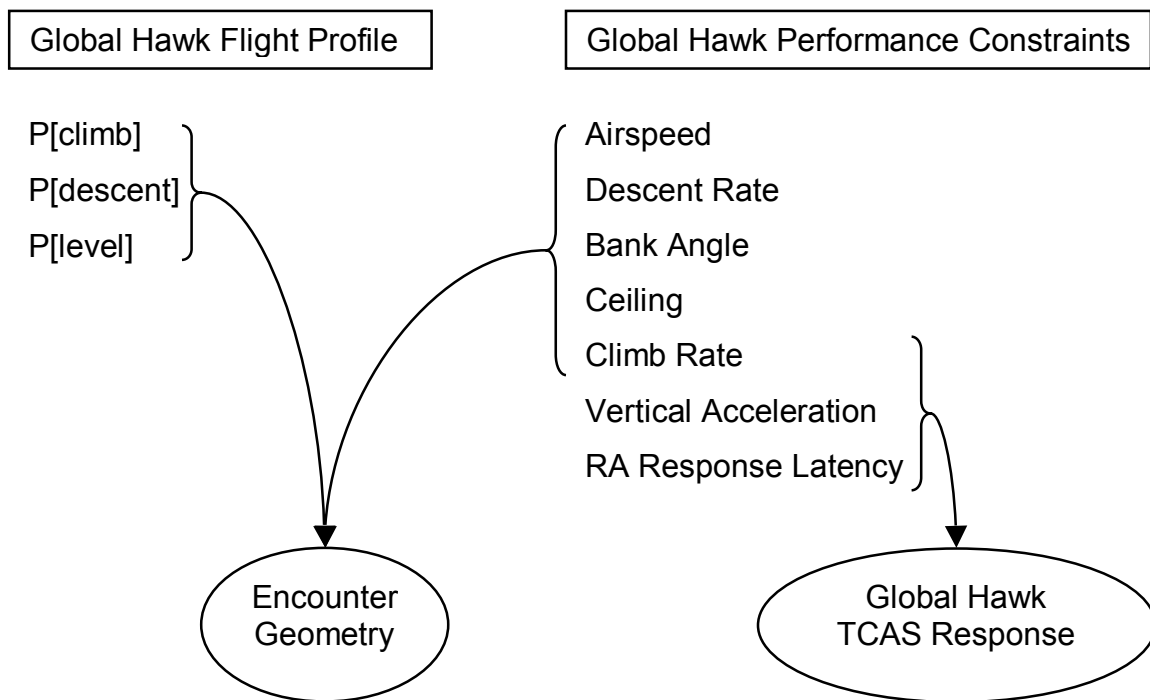


Figure 2-23: Summary of Global Hawk Effects on Encounter Generation and Simulation

3. Simulation Results

Having described the method for airspace encounter model use and the generation of Global Hawk-specific encounter models, this section presents the results of the simulation of millions of two-aircraft encounters using the Global Hawk models.

A total of 1,860,000 runs were simulated for each test condition (described in Section 3.1) using the Global Hawk modified ICAO model, 310,000 runs in each of six altitude layers. For the European model, 1,000,000 runs were simulated for each test condition, 200,000 runs in each of the five altitude layers.

3.1. Test Conditions

All simulations involved two aircraft. The first was always a conventional aircraft with flight characteristics based on the original ICAO or European encounter model and equipped with and responding to TCAS. The second aircraft was controlled to be either a conventional aircraft or Global Hawk. By changing the aircraft's flight characteristics, whether it had TCAS onboard, or how it responded to TCAS resolution advisories, multiple effects on risk ratio could be observed. Several combinations of encounter model, aircraft response and equipage were used; these are shown in Table 3-1 and described below.

Table 3-1: Simulation Parameter Combinations

<i>TCAS-Equipped Conventional Aircraft vs.</i>		
Encounter Model	TCAS Response	Equipage
ICAO	Conventional	Mode S Transponder
Global Hawk-Modified ICAO	Global Hawk	TCAS
European	Global Hawk + Delay	
Global Hawk-Modified European		

Encounter Model:

The original ICAO and European encounter models were modified as discussed in Section 2.2 to develop models for Global Hawk. Two Global Hawk models were created, one based on the ICAO model and the other based on the European model. Simulations were run for the ICAO and European model encounters and for the two Global Hawk model encounters, and risk ratios were then compared. This allowed the effect of Global Hawk's vertical flight profile and performance constraints on risk ratio to be observed.

TCAS Response:

A *conventional* TCAS response indicates that during the simulation, the aircraft responded to TCAS with a vertical acceleration and climb rate that met the requirements discussed in Section 2.2.3 and 2.2.7 (0.25g and 1500 ft/min for an initial RA, and 0.35g and 2500 ft/min for a strengthened RA). The RA latency for a conventional response is 5 seconds for an initial RA and 2.5 seconds for a subsequent RA. A *Global Hawk* TCAS response indicates that limits were imposed on climb rate and vertical acceleration that could prevent the aircraft from meeting the vertical acceleration or climb rate commanded by TCAS. The RA response latency for this condition was still 5 seconds (initial) and 2.5 seconds (subsequent). The third type of TCAS response, *Global Hawk + Delay*, indicates an additional latency in the response to resolution advisories. This represents a total latency caused by round-trip communication delays in addition to human operator response delays. The delays for both initial and subsequent RAs were increased by 5, 10, and 15 seconds so that the final set of encounters had Global Hawk responding with a 20 second initial RA latency and 17.5 second subsequent latency. In addition, a set of encounters was simulated with no delay in response to either an initial or subsequent RA, in order to represent a best-case, automated response to TCAS on Global Hawk.

Equipage:

The equipage on Global Hawk was set to be either a *Mode S transponder* alone or in combination with *TCAS*. During cases where Global Hawk was only equipped with a Mode S transponder, the only avoidance maneuver commanded or performed was by the other aircraft, equipped with TCAS. Risk ratio would therefore generally be higher for these cases than for those where both aircraft are TCAS-equipped.

3.2. Results

The following figures show two types of effects. First, the effect on risk ratio of equipping both aircraft with TCAS (instead of Mode S vs. TCAS) is highlighted by comparing the heights of a red and a blue bar at a given altitude layer. Second, the effect of Global Hawk's encounter model and TCAS response on risk ratio is shown by comparing the first pair of bars to the second pair at a given altitude layer. The results are presented in this way for both the ICAO and European encounter models. The description of what each bar represents is annotated for only one altitude layer in the figures, but applies to all other layers as well.

3.2.1. ICAO Encounter Model

Figure 3-1 shows the results for the ICAO encounter model and the Global Hawk modified ICAO model with one aircraft carrying a Mode S transponder alone (red bars) and then TCAS (blue bars). All of the simulated encounters were run versus a conventional TCAS-equipped intruder aircraft. The first two bars (light red and light blue) represent the improvement TCAS provides to a conventional aircraft. The second two bars (dark red and dark blue) represent this same effect using the Global Hawk modified encounter model.

TCAS decreases the risk ratio by more than 75% from the Mode S value at all altitude layers in the original ICAO model. TCAS does not perform as well against an unequipped intruder performing a climb or descent as it does when the intruder is level. Therefore, because of Global Hawk's higher likelihood of climbing or descending, risk ratio is generally larger for the Global Hawk Mode S case (dark red) than the ICAO (conventional) Mode S case (light red). This is the case in the first four altitude layers. However, at layers five and six, the risk ratio when Global Hawk is unequipped with TCAS decreases from that of a conventional aircraft. The most likely reason for this is that at high altitude layers, although Global Hawk has a higher likelihood of climbing, it also climbs at slower vertical rates than a conventional aircraft. Since Global Hawk's climb rate is not as high at these altitudes, TCAS would be more effective against a Global Hawk aircraft unequipped with TCAS than against an unequipped conventional aircraft.

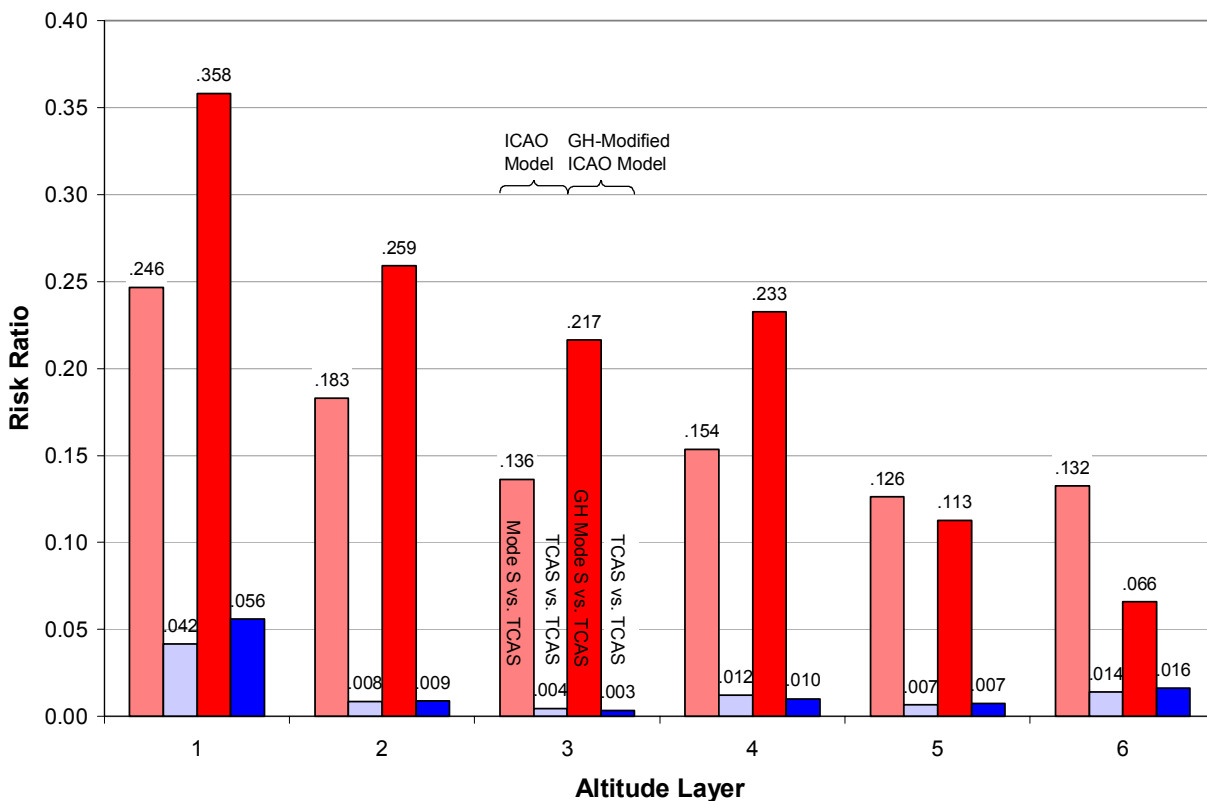


Figure 3-1: Risk Ratio Comparison, ICAO Model vs. Global Hawk-Modified ICAO Model

Equipping Global Hawk with TCAS in addition to a Mode S transponder significantly reduces risk ratio at all altitude layers in the modified ICAO encounter model.

The differences in risk ratio between altitude layers are primarily due to variations in the encounter geometries that are dependent upon altitude. For instance, aircraft vertical profiles, horizontal accelerations and closure angles are different at high altitudes than at lower altitudes due to the statistical distribution of the collected radar data used to generate the encounter models. These combined changes can cause risk ratio to increase or decrease with altitude layer in both encounter models.

Figure 3-2 shows the results for the Global Hawk RA latency study. Risk ratios are shown for cases where Global Hawk initial RA response times were increased from zero seconds (autonomous) to twenty seconds. All of the risk ratios are normalized to the Mode S-only risk ratio, where Global Hawk is only equipped with a transponder.

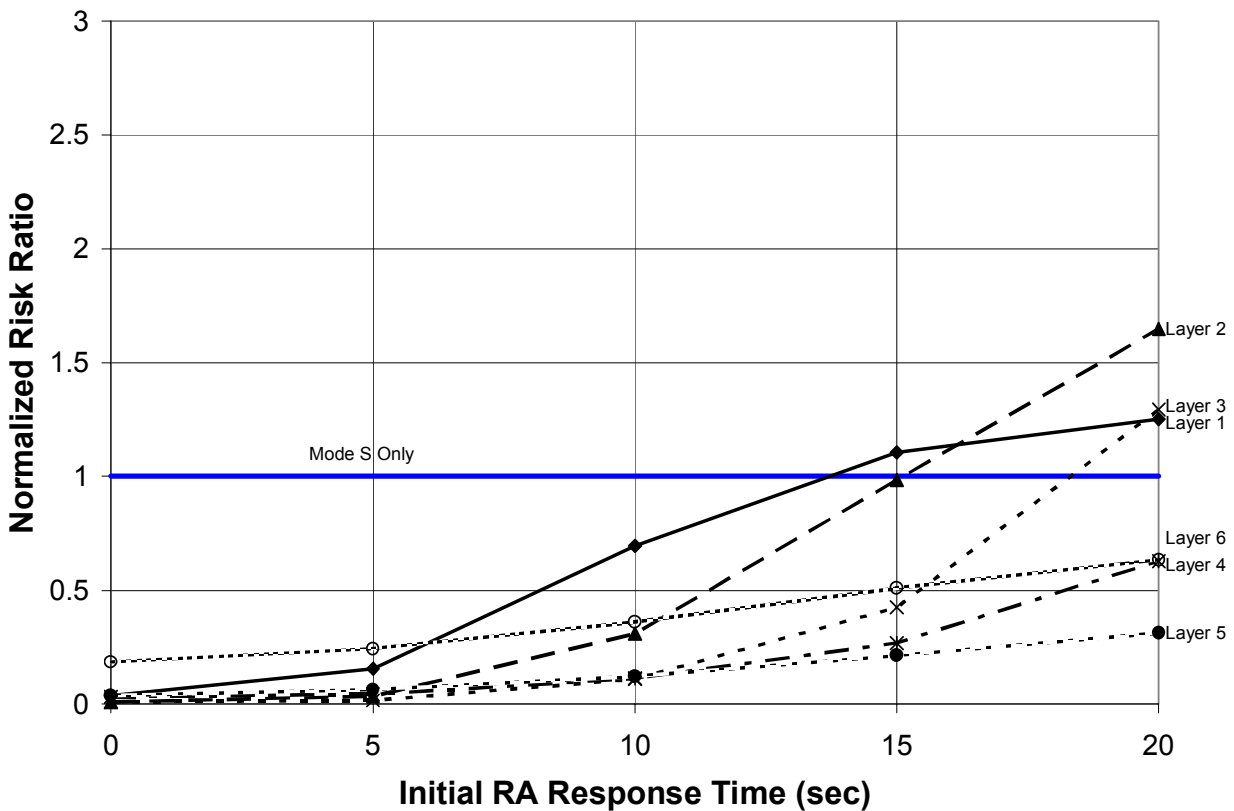


Figure 3-2: Risk Ratio vs. RA Latency, Global Hawk Modified ICAO Model

A response time of zero seconds indicates an autonomous response to TCAS RAs with no delay, and the remaining four points along a given altitude layer line represent 5, 10, 15 and 20 seconds delay between an initial RA and the start of a vertical acceleration in response. The five-second delay case is equivalent to a conventional aircraft pilot response as described in Section 3.1. One important result in Figure 3-2 is the latency allowed before TCAS begins to perform worse than a Mode S transponder alone, which would be indicated by normalized risk ratios greater than one. At altitude layer one the maximum allowable latency appears to be less than 15 seconds. At RA latencies greater than 15 seconds, Global Hawk's initial vertical avoidance maneuver is performed so late that TCAS may have already issued a reversal to the other aircraft, and the two aircraft may actually converge rather than diverge, decreasing the vertical miss distance and hence increasing the probability of an NMAC.

Global Hawk's initial TCAS RA response time was a significant factor in the simulation. After 15-20 seconds delay in RA response, the safety provided by TCAS is much lower than it

would be with a standard five-second pilot response, an autonomous Global Hawk response, or with Global Hawk not even carrying TCAS.

3.2.2. *European Encounter Model*

Figure 3-3 shows the results for the European encounter model and the Global Hawk modified European model. The first two bars represent risk ratios from the original European model with a conventional aircraft response and Mode S transponder equipage (light red), then with TCAS equipage (light blue). The second two bars (dark red and dark blue) are the risk ratios from the Global Hawk modified European model with a Global Hawk aircraft response, also equipped with a Mode S transponder and then with TCAS.

It can be seen that TCAS reduces the risk ratio significantly at all altitude layers for both the European and Global Hawk modified European encounter models. The Mode S risk ratios are higher for the Global Hawk model than for the European model. Like the ICAO model, this is due to the effect of Global Hawk's flight profile (more climbing and descending maneuvers) and performance constraints. Risk ratio is also reduced in the TCAS-equipped case compared to the Mode S-only case.

One significant result is that the risk ratio is greater than 1.0 at altitude layer five for the Global Hawk Mode S-only case (the dark red bar). The mean probability of a mid-air collision with TCAS on the other aircraft increases from what it would be without TCAS. Essentially, at layer five the results indicate that TCAS apparently reduces safety when the intruder aircraft is TCAS-equipped and Global Hawk is only Mode S-equipped. This effect is due to the combination of a peculiarity in the European encounter model and a known vulnerability in the TCAS logic involving slow rate-of-closure encounters [13]. Actual exposure to this risk at high altitudes is believed to be overestimated by the European model and is currently being investigated by other researchers.

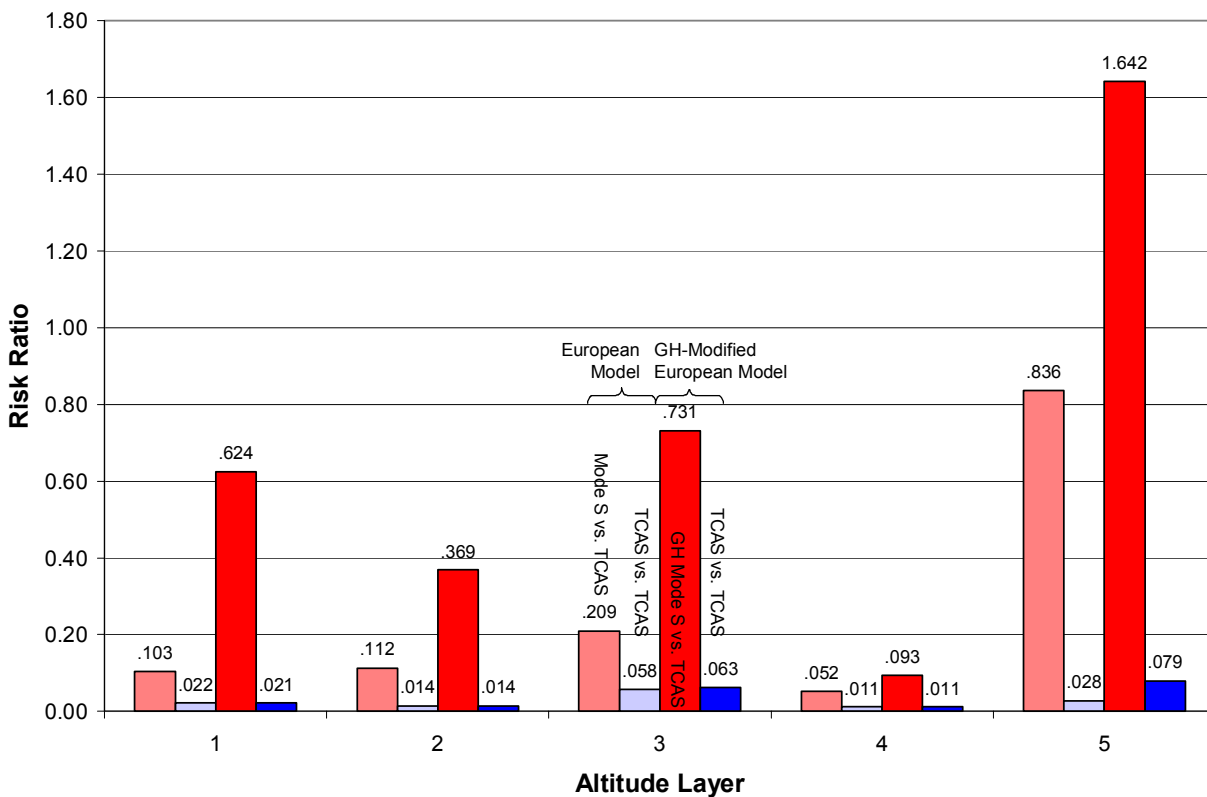


Figure 3-3: Risk Ratio Comparison, European Model vs. Global Hawk-Modified European Model

Figure 3-4 shows the risk ratios for Global Hawk initial RA response times normalized to the Mode S-only risk ratio. The same general observations can be made about RA latency for the Global Hawk modified European model as for the modified ICAO model. A latency of approximately 15 seconds is acceptable before TCAS begins to perform worse than a Mode S transponder alone. By the time Global Hawk reacts to the TCAS RA, TCAS has already determined that the recommended RA is not succeeding, and is likely to have reversed the RA (i.e. “climb” changes to “descend”), with the result that VMD decreases rather than increases.

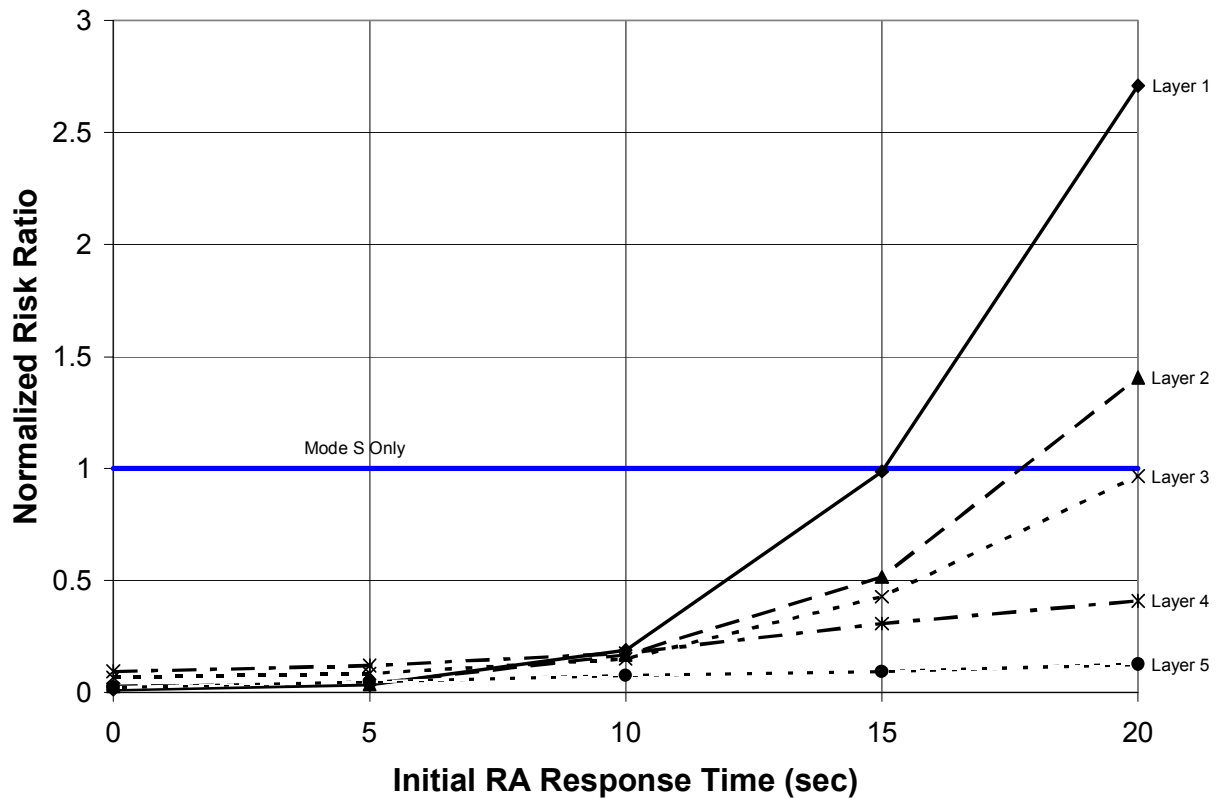


Figure 3-4: Risk Ratio vs. RA Latency, Global Hawk Modified European Model

In order to check the statistical validity of the results presented in this section, a metric called “running risk ratio” can be calculated over a large set of runs. Plotting the running risk ratio allows the risk ratios to be seen converging to statistically stable values as the number of runs increases. To calculate the running risk ratio, the average $P[NMAC\ w/\ TCAS]$ and $P[NMAC\ w/out\ TCAS]$ over the last n simulation runs are computed from $n = 1$ to 200,000.

Figure 3-5 shows the running risk ratio for an example set of 200,000 encounters that were simulated at altitude layer three for the European and Global Hawk modified European encounter models.

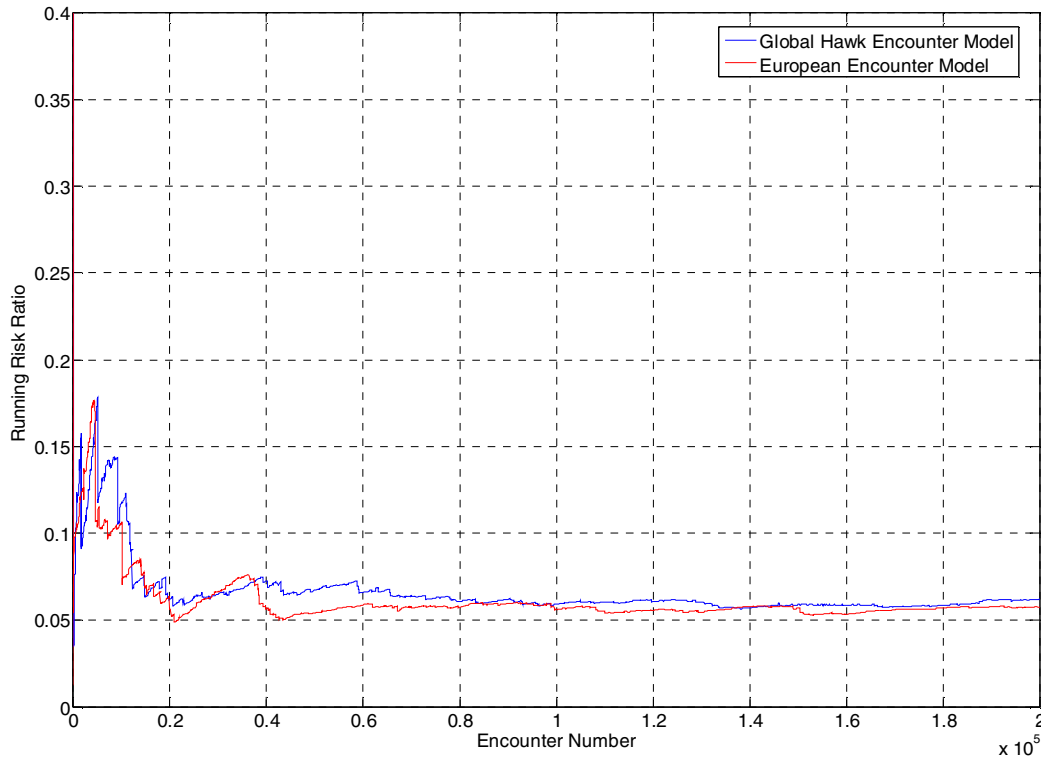


Figure 3-5: Running Risk Ratio, Altitude Layer 3, Conventional TCAS Response

After approximately 40,000 runs, the results begin to stabilize with a consistently higher risk ratio for the Global Hawk modified European model than the conventional European model. The mean difference in running risk ratio when $n = 200000$ is approximately 2σ , where σ is the standard deviation of the risk ratio over the same n . This appears to dominate the effect of noise in the results, so that the higher risk ratio for the Global Hawk model is truly representative of changes in its flight profile, such as the steeper climb and descent rates discussed above. The results indicate that 200,000 is a large enough number of encounters to simulate at each altitude layer in order to obtain statistically valid results.

4. Conclusions and Recommendations

Unmanned aerial vehicles (UAVs) are becoming increasingly important in military and homeland security applications both overseas and domestically. Because of their ability to perform the same mission as manned aircraft without the risk of pilot loss, the number of UAVs operated in the United States will continue to increase in the future. This causes a concern for collision avoidance between UAVs and manned aircraft in civil airspace. The U.S. Air Force's Air Combat Command is seeking to equip the RQ-4 Global Hawk UAV with the Traffic Alert and Collision Avoidance System (TCAS) to address this concern. Since TCAS was not designed for use on UAVs, the level of safety provided by the system must be such that equipping Global Hawk with TCAS would be advantageous.

Two Global Hawk-specific encounter models were constructed to help evaluate TCAS effectiveness. One was based on a European Airborne Collision Alerting System Analysis (ACASA) traffic model and the other was based on a model defined by the International Civil Aviation Organization (ICAO). The Global Hawk encounter models reflected two types of modifications: one from Global Hawk's flight profile that included limits on several flight parameters such as airspeed and climb rate, and the other that affected the mixture of encounters, i.e. how often a climbing or descending vertical maneuver was selected for Global Hawk. Global Hawk's climb rate and vertical acceleration limits were also imposed in the dynamic simulation to observe how its response to TCAS would be different than a conventional aircraft.

4.1. *Global Hawk Flight Profile*

Global Hawk's vertical profile can raise or lower risk ratio, depending on which encounter model was used and the altitude layer in which the encounters were simulated. At high altitudes in the modified European encounter model, the risk ratio increased from that of two conventional aircraft, both for the TCAS-equipped and the Mode S-equipped Global Hawk cases. For the case where Global Hawk was equipped with only a Mode S transponder, the risk ratio rose to approximately 1.6 even with TCAS on the intruder aircraft. The risk ratio of 1.6 indicates a 60% safety degradation with TCAS, as opposed to an expected increase in safety. This is due to an issue in the European encounter model which involves a particular vulnerability

in TCAS during slow rate-of-closure encounters, rather than a prediction of unsafe operations [13].

In the modified ICAO model, the changes to risk ratio due to Global Hawk's flight profile were not nearly as drastic. These results indicate that although the flight profile of Global Hawk does have some effect on risk ratio, the effect is not widespread across both encounter models. Additional testing could include a study of how Global Hawk's proportion of continuous climbing or descending vertical maneuvers affects risk ratio. 80% was selected as a reasonable estimate for this number, but radar data or the aircraft's flight data recorder may indicate a number that is higher or lower. New sets of encounters could be generated and simulated that reflect an increase or decrease in this number, as well as its effect on risk ratio.

4.2. TCAS RA Response Latency

TCAS simulations using both the modified European and ICAO encounter models indicate that there is room for approximately 15 seconds of communication latency before TCAS performs worse than not having TCAS on Global Hawk. Especially at lower altitude layers, risk ratio begins to rise rapidly after an RA response time of more than 5-10 seconds. An autonomous RA response for Global Hawk appears to be a promising solution. With an immediate RA response time, the simulations gave a maximum risk ratio of just 18.5% of the Mode S-only value for the modified ICAO model and 9.5% for the modified European model.

4.3. Global Hawk Vertical Acceleration and Climb Rate Limits

Global Hawk's vertical acceleration and climb rate limits during the simulation appear to have a slight effect on risk ratio. The effect was limited primarily to altitude layer one of the modified ICAO encounter model. As discussed in Section 2.2.7, this effect is due to the slower airspeeds flown by Global Hawk at lower altitudes that at times prevented it from reaching the vertical acceleration commanded by TCAS. At the higher altitude layers, the climb rate limit had only a slight effect on risk ratio. The increases were much smaller for the modified European model, and in general none of the increases were causes for concern. TCAS does have the capability to inhibit the climb or increase climb RA rate limits due to high altitude or aircraft configuration [6]. This capability was not studied for Global Hawk, and because of the very small change the climb rate limit has on risk ratio, this may not be an issue warranting further

investigation. The effect of Global Hawk's vertical acceleration limit on its ability to respond properly to TCAS RAs needs to be discussed with the TCAS community.

4.4. Summary and Recommended Research

The results of the dynamic simulation conducted for Global Hawk indicate that a significant improvement in safety is provided by equipping the aircraft with TCAS in addition to the Mode S transponder it currently has. Risk ratios from the TCAS-equipped cases lie in the range of 0.003 – 0.079, compared to 0.004 – 0.058 for conventional aircraft. Several important matters remain to be studied and tested.

One issue that needs to be resolved is how the actual communication latency will affect Global Hawk's response to a TCAS RA in LOS and BLOS ranges of its command and control equipment. A pilot response delay adds to the total communication latency: the current TCAS procedure for manned aircraft is to disengage the autopilot and take manual control in response to an RA. Because Global Hawk does not have standard flight controls, as discussed in Section 1.2, the process of responding to RAs would be different than a manned aircraft and may result in an increased total round-trip delay time. The maximum value for the total delay time could provide insight as to whether TCAS would improve or degrade safety, if pilot response to TCAS is selected as a collision avoidance solution. If the delay is greater than 15 seconds, an alternative solution appears to be integrating TCAS into Global Hawk's flight management system and programming it to respond autonomously to RAs.

Another important issue for UAVs in general and for Global Hawk in particular, is the lack of visual acquisition capability for collision avoidance and how to resolve this. Several systems are currently being studied for use in combination with TCAS, either to increase pilot situational awareness on the ground or to assist in autonomous collision avoidance.

TCAS failure modes must be analyzed carefully as well. A fault tree can be constructed to pinpoint particular sources of failure and identify how each source contributes to the overall probability of system failure and its impact on safety.

The tools used for this thesis focused on the analysis of close encounters between two aircraft. There may also be situations where Global Hawk encounters multiple manned aircraft while flying in the National Airspace System (NAS). A separate analysis still needs to be

performed that examines the likelihood and criticality of multiple-aircraft encounters that may occur.

Civil airspace has changed in several important ways in recent years. Aircraft types, speeds, accelerations, approach patterns, and density have all affected how aircraft encounter each other in civil airspace. For example, a program called Reduced Vertical Separation Minimum (RVSM) was implemented by the FAA in domestic airspace. RVSM reduces the minimum vertical separation requirement from 2000 ft to 1000 ft at higher altitudes, thereby enhancing airspace capacity by enabling aircraft to operate at additional flight levels. New radar data needs to be collected to develop an encounter model that is more reflective of the types of two-aircraft encounters that occur in the NAS. Once an updated encounter model is developed, additional analysis of TCAS on Global Hawk can be performed.

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