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COVER SHEET

Access 5 Project Deliverable

Deliverable Number: *CCA004-Rev5*

Title: *Updated CCA Safety Analysis*

Filename: *CCA004_CCA Safety Report _Rev5_FINAL.pdf*

Abstract:
This document describes a method to demonstrate that a UAS, operating in the NAS, can avoid collisions with an equivalent level of safety compared to a manned aircraft. The method is based on the calculation of a collision probability for a UAS , the calculation of a collision probability for a base line manned aircraft, and the calculation of a risk ratio given by:
Risk Ratio = P(collision_UAS)/P(collision_manned).
A UAS will achieve an equivalent level of safety for collision risk if the Risk Ratio is less than or equal to one. Calculation of the probability of collision for UAS and manned aircraft is accomplished through event/fault trees.

Status:

TBD

Limitations on use:
Some of the probability values assigned to the nodes in the event trees are estimations and must be validated based on analysis, simulation and/or flight experiments. The risk ratio is calculated for the baseline of a manned aircraft without collision avoidance on-board. The collision probability calculations are for the own ship, manned and unmanned, to avoid the traffic aircraft. It does not take into account the capability of the traffic aircraft to avoid the own ship.

[redacted]

NASA ACCESS 5

Sense and Avoid Safety Analysis for Remotely Operated Unmanned Aircraft in the National Airspace System

The following document was prepared by a collaborative team through the noted work package. This was a funded effort under the Access 5 Project.

Version 5
13 February 2006

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NASA ACCESS 5
Work Package 2, Collision Avoidance

[redacted]

Acknowledgments

Contributing to the work reported in this document are Won-zon Chen, Jan DeLuca, Andy Zeitlin, Duane Ludwig, and Russ Wolfe. Special thanks to Stephen George for discussions and guidance.

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Executive Summary

The Access 5 program objective is to develop methods and guidelines to routinely operate unmanned aerial vehicles in the National Airspace System (NAS), similar to manned aircraft flight. To achieve the objective of routine operations of Unmanned Aircraft System (UAS) in the NAS, UASs must integrate safely into the NAS while causing the minimum impact on the existing system.

Operation of a UAS in the NAS requires that the aircraft perform a set of functions which will meet mission objectives. A critical element of these functions is to sense and avoid other traffic in the airspace. Manned aircraft operating in the NAS have a low risk of mid air collision due to a multilayer approach to collision avoidance. These layers consist of operational procedures, Air Traffic Control services, on-board collision avoidance systems, and see and avoid.

This document describes a method to demonstrate that a UAS, operating in the NAS, can avoid collisions with an equivalent level of safety compared to a manned aircraft. The methods is based on the calculation of a collision probability for a UAS, the calculation of a collision probability for a baseline manned aircraft, and the calculation of a risk ratio given by:

Risk Ratio = P(collision_UAS)/P(collision_manned)

A UAS will achieve an equivalent level of safety for collision risk if the risk ratio is less than or equal to one.

Calculation of the probabilities of collision for UAS and manned aircraft are accomplished through an event/fault tree. Node probabilities of the event/fault trees are based on historical data, previous safety studies, operational data, discussions with pilots and aviation experts, simulation experiments, flight tests, and analysis. Event trees are included in this document representing some candidate sense and avoid configurations.

1. Introduction

1.1 Purpose

The purpose of this report is to describe a safety analysis method to estimate the relative risk of collision of an Unmanned Aircraft System (UAS) in the National Airspace System (NAS), as compared to a manned aircraft. Safety and risk ratios are based on the calculation of the probability of a Mid-Air Collision (MAC). The safety analysis also evaluates the sensitivity of the factors contributing to the collision probability. An event/fault tree is used to calculate MAC probabilities. Two representative event trees are included in this report.

1.2 Scope

The safety analysis in this document addresses risk of collision of UASs in the NAS operating in class A airspace. It considers the probability of collision under non failure conditions and under some failure conditions that directly affect the collision avoidance functionality. The collision probability calculation does not consider failure conditions such as engine failure, hydraulic system failure, structural failure, etc. These failure conditions and the hazards associated with them will be addressed elsewhere by the Access 5 Reliability Work package.

Probability of MAC is estimated using event/fault trees. The probabilities of occurrence of primary events will be obtained, calculated, or estimated using historical data, previous safety studies, existing operational data, analytical methods, simulation and flight test. The event trees include physical and operational components. The example event trees included in this report estimate the probability of MAC for UASs using Mode-S/directional antenna surveillance and GPS/ADS-B surveillance with Access 5 developed collision avoidance logic. It must be noted, however, that the Access 5 project is not proposing or endorsing the use of Mode-S/directional antenna and/or GPS/ADS-B as the solution system for UAS sense and avoid.

1.3 Objective

Estimation of MAC probabilities for various collision avoidance and surveillance systems will complement the definition of Equivalent Level of Safety (ELOS) defined in “ELOS Comparable to See-and-Avoid Requirements for Manned Aircraft” [8]. It will provide a quantified evaluation of collision avoidance and surveillance systems. It will be used to support the development of functional requirements and reliability requirements. The MAC probability estimation is performed in the context of an operational environment and using assumptions from the proposed concept of operations. A MAC, as defined in section 1.5, provides a geometrical characterization to be used in simulation and analytical studies. A MAC has been defined such that any encounter of this nature between aircraft is considered a catastrophic event. No attempt is made to characterize the geometry or contact points of a collision, possibility of surviving a collision, or other lower level details.

1.4 Project Sponsors and Participation

The Access 5 project is sponsored by the National Aeronautics and Space Administration (NASA). The Access 5 Project Office is located at NASA Dryden Flight research Center, Edwards, California. This report contains work performed under the Collision Avoidance Work Package 2, Safety Analysis Task.

1.5 Definitions

- Mid-Air Collision (MAC) – An encounter between aircraft that results in a separation from center of gravity to center of gravity of 200 feet or less horizontally and 65 feet or less vertically. See Section 2.5.1.

- Critical Near Mid-Air Collision (NMAC) is defined as separation distance center of gravity to center of gravity of 500 feet or less horizontally and 100 feet or less vertically [4, 9]. A Near Mid-Air Collision has also been defined in references [16, 17] as "proximity of less than 500 feet to another aircraft" which is interpreted as the closest distance between aircraft structures.

- Proximity Trajectory – A trajectory in which two aircraft will have a separation of one half (½) nautical mile or less horizontally and 500 feet or less vertically at the closest point of approach. This trajectory is defined as an encounter in which there is a possibility of a pilot identifying the traffic aircraft as a collision threat and taking evasive action which might lead to an induced collision. The closest point of approach distance is deliberately selected as a large distance to include any induced collision possibility. It is assumed that trajectories with a larger separation at the closest point of approach do not represent a credible threat for an induced collision.

- RA encounter – An encounter between aircraft that would result in a resolution advisory from an operational TCAS II in one or both aircraft. Since the sensitivity of TCAS to issue RAs is selectable, an RA encounter cannot be directly associated with an encounter geometry. In many cases, an encounter in which an RA is issued will result in a NMAC if no changes in trajectories are performed. However, there are cases in which an RA is issued and no NMAC will result even if no evasive action is taken. For the purposes of analysis, an encounter between aircraft that does not result in an RA because the TCAS is not operating or installed, is still consider an RA encounter if an operational TCAS would have issued an RA.

[redacted]

• Separation – The standard en-route distances that two aircraft must maintain as dictated by the FAA. Typical distances are 5 Nautical Miles horizontally and 2000 feet vertically; 1000 feet vertically for Reduced Vertical Separation Minima (RVSM). No separation standard distance applies to VFR flight.

• Loss of separation – Current violation of separation minima (time = 0).

• Conflict – A predicted loss of separation. The trajectories of the aircraft are such that a loss of separation will occur in the future (time > 0).

2. Mid-Air Collision Probability Estimation

The estimation of the probability of MAC is based on an event/fault tree analysis. The estimation is based, as far as possible, on a generic remotely operated aircraft, making minimum assumptions on the system implementation. The generic concept of operations and list of assumptions are included in this section. Each of the primary event probabilities will be calculated or assigned a value and the rationale for the values will be discussed.

2.1 Risk Ratio Method

One of the objectives of the Access 5 project is to determine the capabilities and requirements of UASs to assure that the risk of collision is no higher than for manned aircraft. The overall collision probability of an aircraft in the NAS depends on several factors including operational procedures, type and density of airspace, type and size of aircraft, air traffic control services, weather, etc. Figure 2.1 depicts the predominant layers in the NAS to prevent mid air collisions. Note that not all manned aircraft are required to have on-board Collision Avoidance Systems (CAS) and that implementations of UASs might or might not have CAS logic at the control station.

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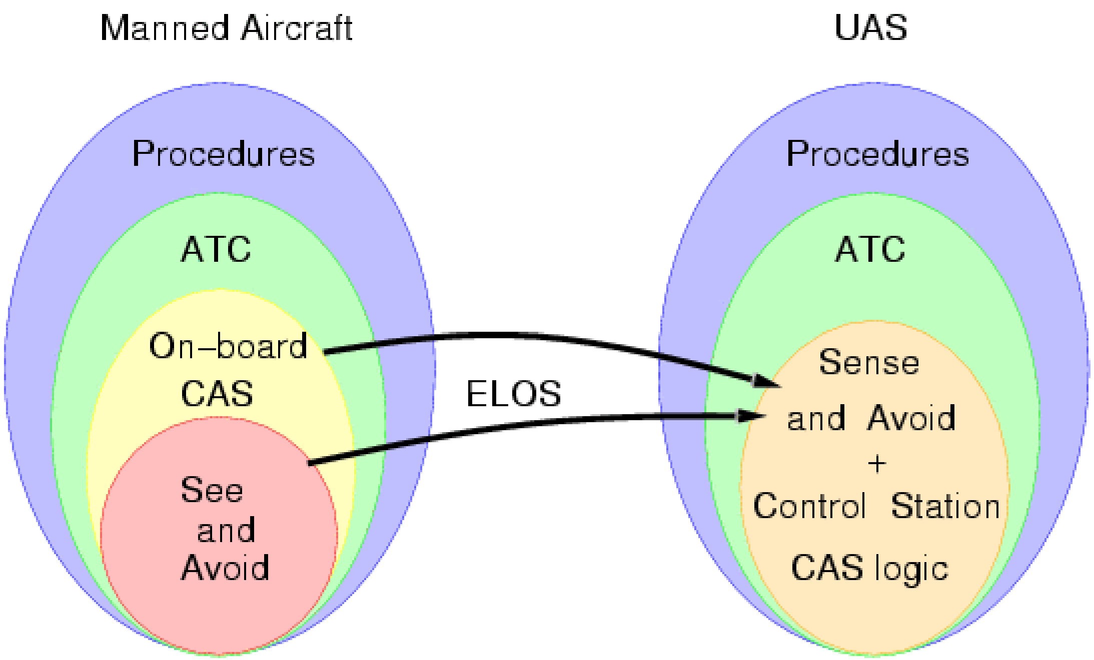

Figure 2.1. Primary Layers in the NAS to Prevent Mid Air Collisions.

The method used to assess the collision avoidance capability of a remotely operated aircraft is to calculate a risk ratio. The risk ratio is the probability of collision per encounter of a UAS divided by the probability of collision per encounter of a manned aircraft. The risk ratio calculations in this report, Section 5, are for manned aircraft without collision avoidance equipment on-board. However, the event trees and the analysis structure include nodes and events which can be used to calculate a risk ratio including collision avoidance equipment on-board the manned aircraft.

For the purpose of this safety study, the assumption is made that such factors as procedures and ATC services will contribute equally to the prevention of a collision for manned aircraft than for a UAS. Therefore, the risk ratio is based on the comparison of the see-and-avoid factor for a manned aircraft and the sense-and-avoid factor for UAS.

The assumption that procedures and ATC services contribute equally to collision avoidance for UAS and manned aircraft is not necessarily a sound assumption. This will be addressed by further studies and simulations. Specifically, the simulation work package is developing comprehensive simulations which model the interaction of UAS, ATC, and other NAS users and operators.

2.2 Concept of Operation

A generic concept of operation is used to identify which parts of the system can have an impact on the collision avoidance functionality of the UAS. The operation of the UAS is depicted in Figure 2.2.

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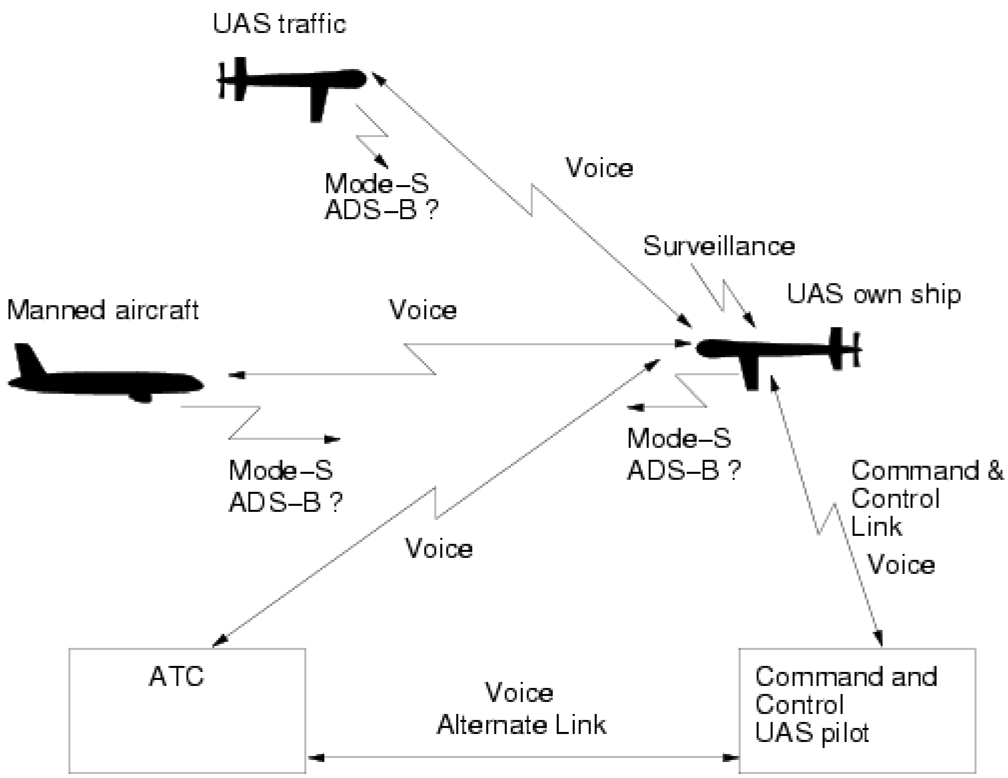

Figure 2.2. Functional Representation of UAS Operation.

The aircraft is controlled from a ground/airborne Command and Control Center. A command and control (CC) link sends commands to the aircraft and receives status data from the aircraft including surveillance, systems status, location, flight parameters, and other. Voice communication between the UAS, ATC and traffic aircraft is relayed to the command and control center via the CC link, a separate link, or both. The CC link and the voice relay link could be implemented by a single link or by redundant and possibly dissimilar communication systems.

The UAS is equipped with a Mode-S transponder. The manned aircraft, the UAS own ship and the UAS traffic might or might not have ADS-B capabilities. Depending on the implementation, the surveillance of the UAS own ship could be a variety of technologies including radar, infrared, optical in the visual spectrum, TCAS surveillance, ADS-B reception, TIS-B reception, or a combination of these or other technologies. The safety analysis can be used to determine the impact of these technologies on the overall collision risk and evaluate the alternatives.

[redacted]

2.3 Assumptions

The assumptions listed in this section are for the purpose estimating basic event probabilities. They do not reflect the operational guidelines and procedures that could result from the Access 5 project or other previous or current work.

- The UAS is assumed to operate in the NAS without any special operational procedure distinct from manned aircraft. No segregation between UAS and manned aircraft is performed.

- The UAS aircraft is Mode-S equipped. The Mode-S transponder might or might not have extended broadcast capability with ADS -B data.

- All traffic in the UAS operational environment are Mode-S equipped. Traffic aircraft might or might not have Mode-S transponder with extended ADS-B broadcast capabilities.

2.4 Event /Fault Tree

The event/fault tree is composed of a set of basic (primary) events, probabilistic association of events represented by logic functions, and compound events that result from basic events or other compound events. The top-level event gives the probability of a Mid-Air Collision between two aircraft given that these aircraft are in a collision course or proximity course and does not take into account the collision avoidance capability of the traffic aircraft. That is, the collision avoidance calculation is only based on the capabilities of the ownship. The probabilistic gates used in the event tree are:

- AND – An event occurs if and only if all its sub-events occur. The probabilistic AND calculation is the product, P1 x P2, of the input events.

- OR – An event occurs if any or all of its sub-events occur. The probabilistic OR calculation is the sum minus the product, P1 + P2 – P1xP2, of the input events. In the case of a 3 input OR, the probability is given by:

  $$P1 + (P2 + P3 - (P2xP3)) - P1x(P2 + P3 - (P2xP3))$$

  distributing and rearranging,

  $$P1 + P2 + P3 - P1xP2 - P1xP3 - P2xP3 + P1xP2xP3$$

- XOR – (exclusive or) An event occurs if any of its sub events occur. The sub-events are mutually exclusive; that is, they cannot occur simultaneously. The probabilistic XOR calculation is the sum, P1 + P2, of the input events. An example of mutually exclusive events: P1, On MAC trajectory, P2, Not on MAC trajectory.

2.4.1 Top Level Tree

The top level tree, shown in Figure 2.3, is common to the manned aircraft see-and-avoid and to the UAS sense-and-avoid function.

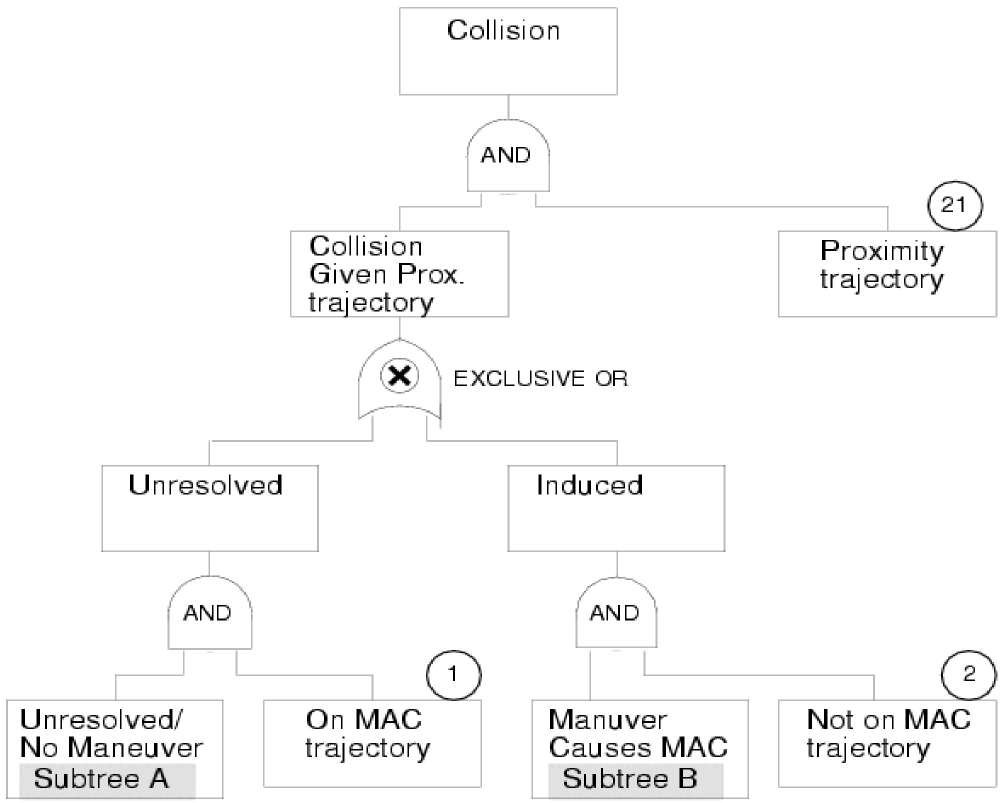

Figure 2.3. Top Level Tree Common to Manned and Unmanned Aircraft.

The probability of a Proximity trajectory when in an en-route environment is the probability that procedures in the NAS and air traffic control services have failed to maintain the required separation between aircraft. To calculate a risk ratio between manned and unmanned aircraft, this probability is set to 1. See Section 2.5.3 for a detailed discussion.

The events <u>On MAC trajectory</u> and <u>Not on MAC trajectory</u> are the geometric probabilities that given a Proximity trajectory, the trajectory is a MAC trajectory or not. These nodes are mutually exclusive and their values are calculated in Section 2.5.1. Note that a MAC trajectory is a subset of a NMAC trajectory and a NMAC trajectory is a subset of a Proximity trajectory. The event <u>No Maneuver/Unresolved</u> represents the probability that the see/sense and avoid technique will fail to avoid a collision. The event Maneuver Causes MAC represents the probability that the action taken to avoid a collision actually causes the collision where no collision would have occurred had no action been taken. The subtrees which lead to the compound events No Maneuver/Unresolved and Maneuver Causes MAC are specific to the avoidance technique and will be shown in Section 2.4.2 for manned see and avoid and Section 2.4.3 for unmanned sense and avoid.

2.4.2 Baseline Event Subtrees for Manned Aircraft See and Avoid

The baseline event subtrees estimate the probability that a manned aircraft will not avoid a collision (Subtree A, Figure 2.4) and that the avoidance actions by the pilot cause the collision when the aircraft were not in a collision trajectory (Subtree B, Figure 2.5). The probability values for the basic nodes are calculated in the Basic Event section, Section 2.5. The basic nodes are numerically labeled above the node box to match with the probability calculations.

[redacted]

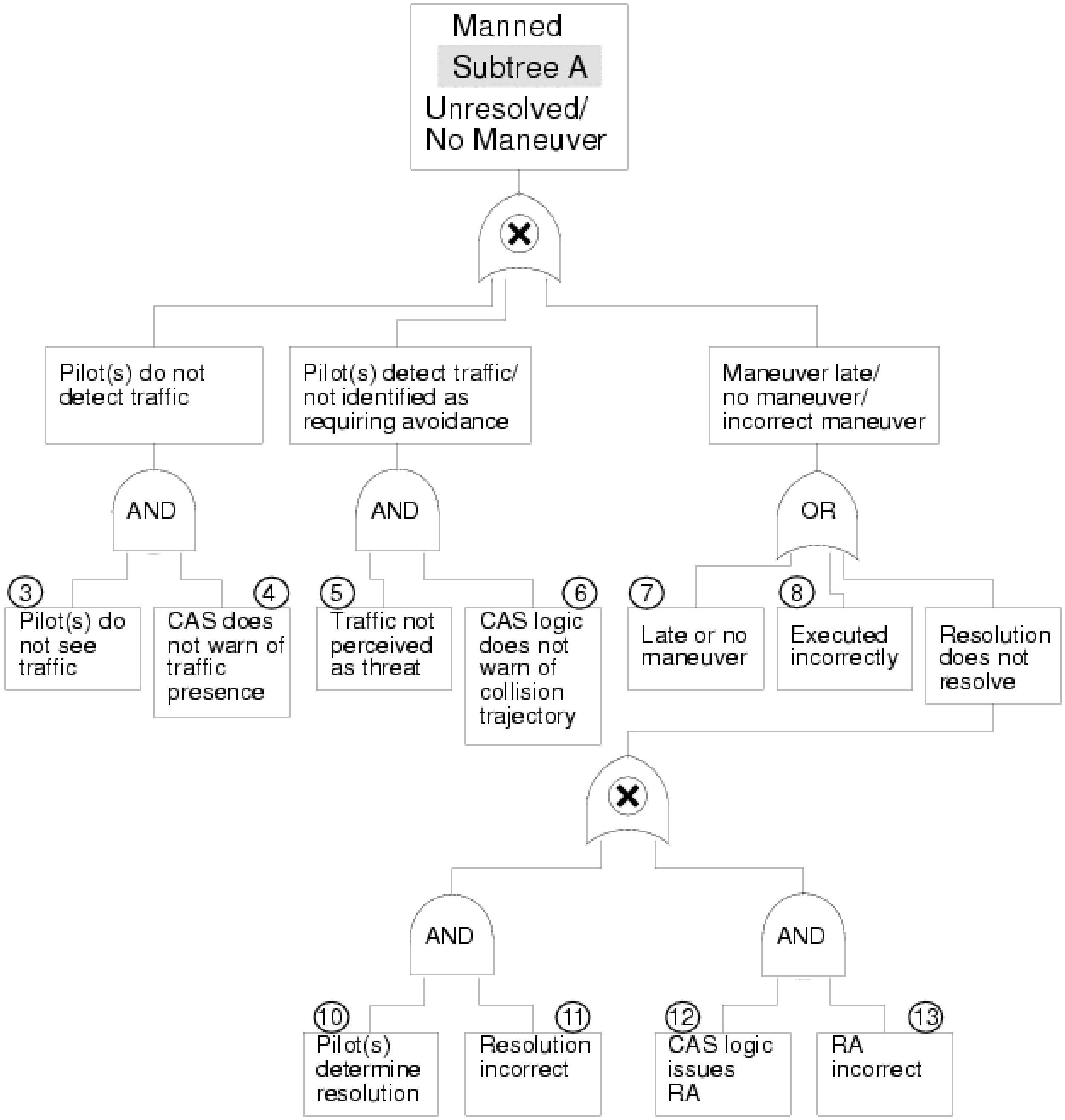

Figure 2.4. Subtree A for Manned Aircraft.

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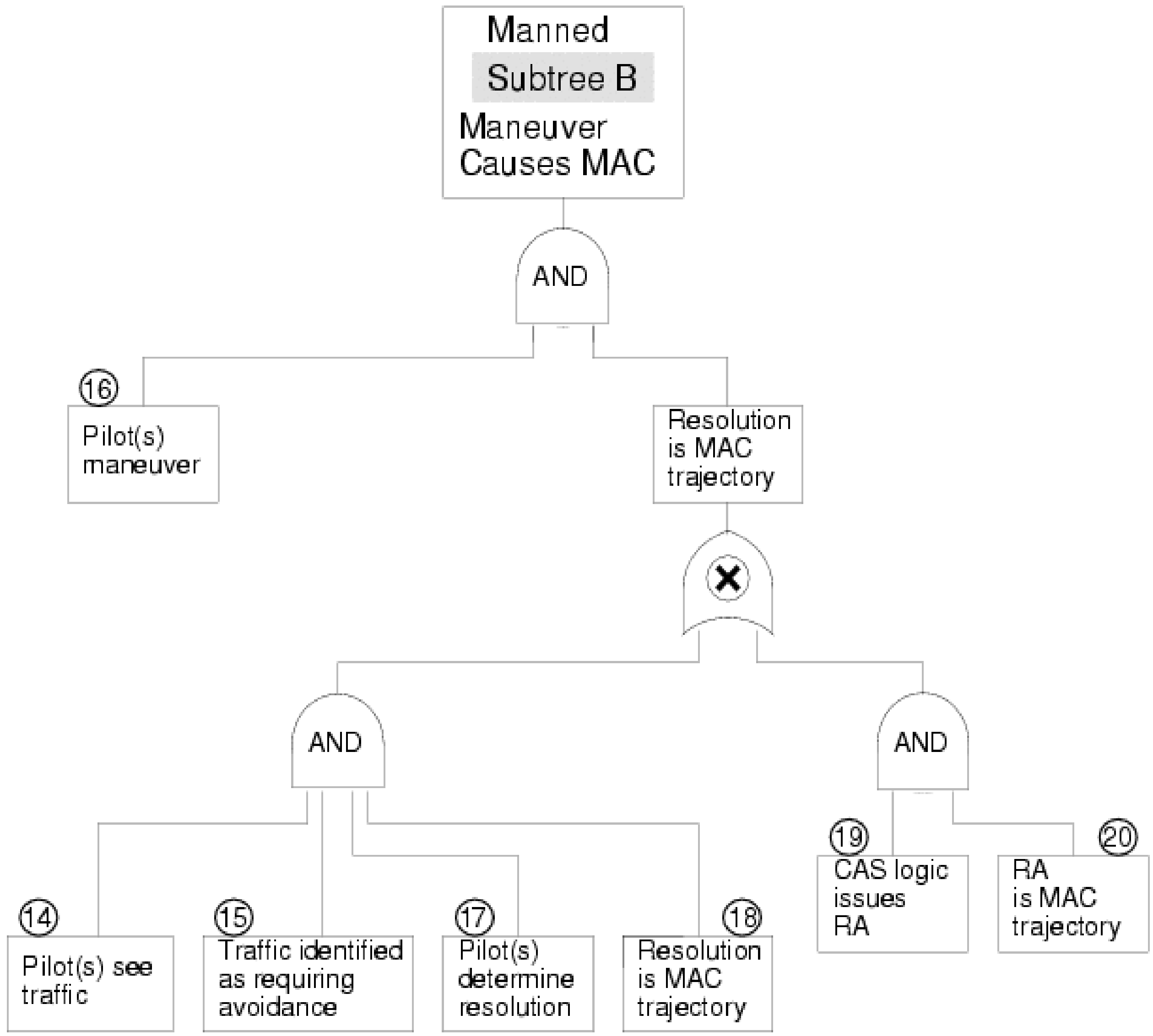

Figure 2.5. Subtree B for Manned Aircraft.

2.4.3 Event Subtrees for Unmanned Aircraft Sense and Avoid

The event subtrees estimate the probability that an unmanned aircraft will not avoid a collision (Subtree A, Figure 2.6) and that the avoidance actions by the pilot cause the collision when the aircraft were not in a collision trajectory (Subtree B, Figure 2.7).

[redacted]

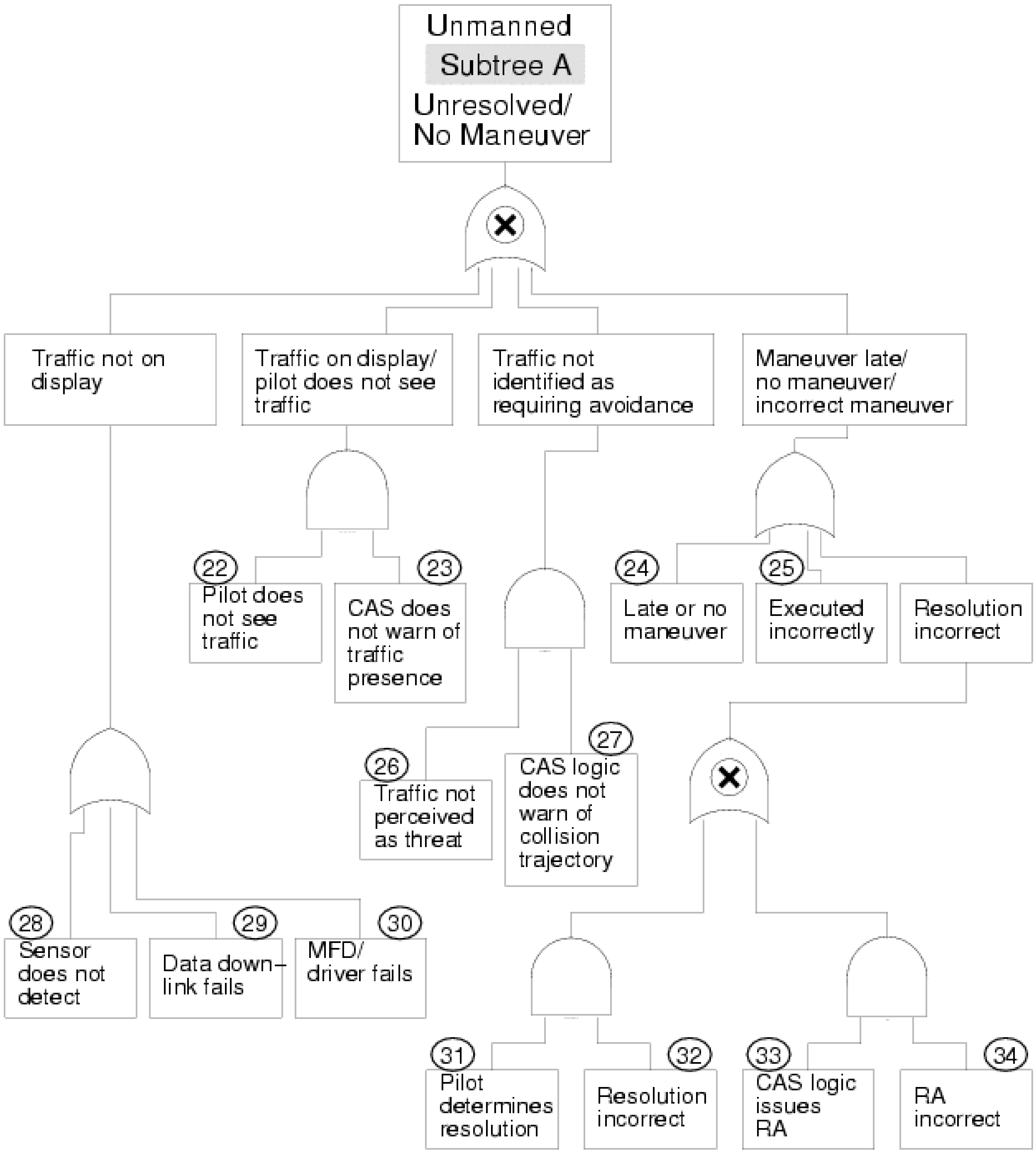

Figure 2.6. Subtree A for Unmanned Aircraft.

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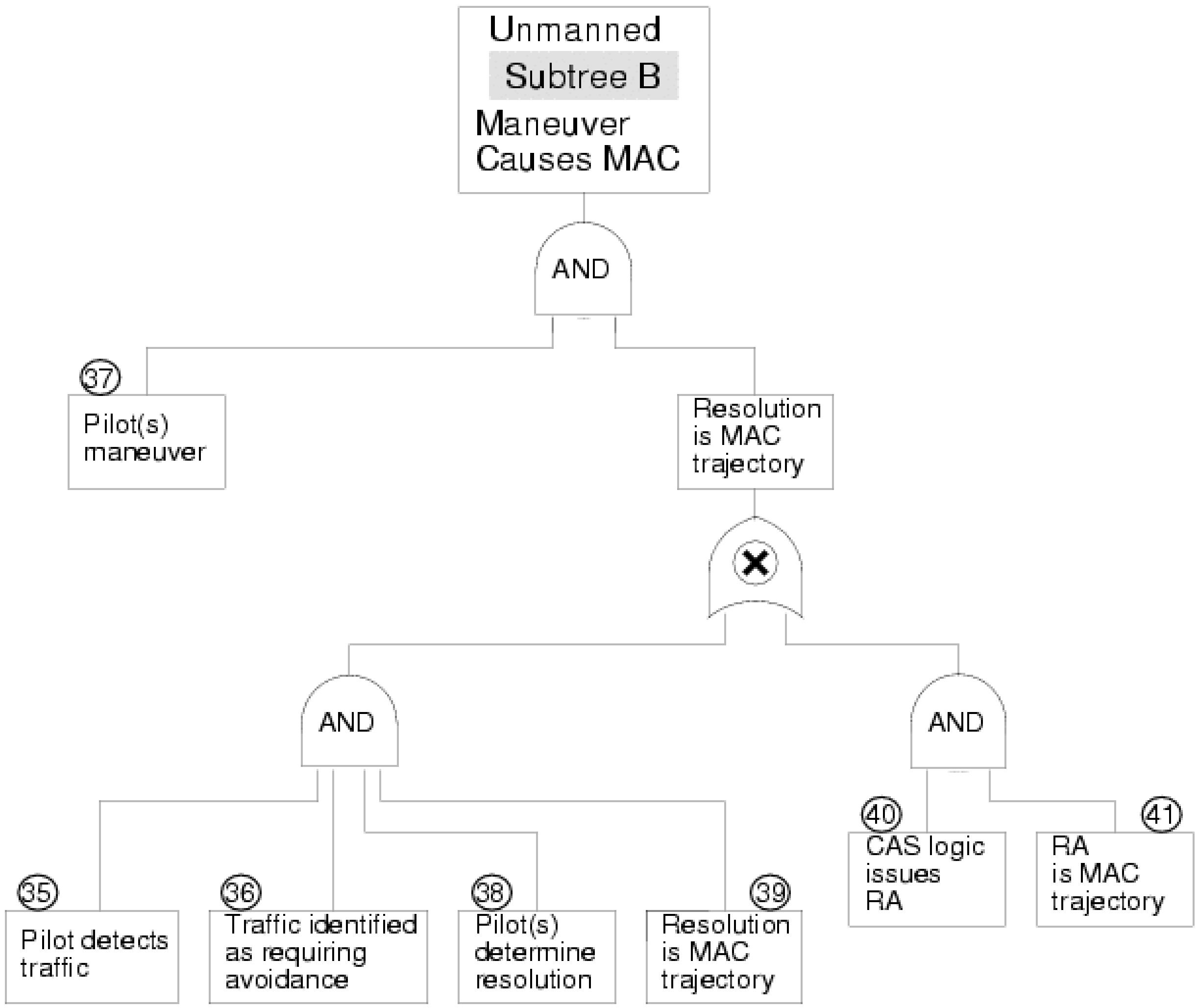


Figure 2.7. Subtree B for Unmanned Aircraft.

2.5 Basic Events

The probability of basic events will be obtained from different sources or calculated. In some instances, the probability will be obtained from simulation and experiments of other Access 5 work package teams. The probability of failure of the command and control link (CC link) is such an example.

The events are classified into geometry, equipment, human factors, and logic events.

[redacted]

2.5.1 Geometry Events

Geometry events comprise events that mostly result from the physics of the encounter. Inevitably, there will be some secondary effects. For example, the probability of visual acquisition is directly affected by the geometry of the encounter. However, since the primary factor for visual acquisition is the pilot, this event is grouped under the human factor events.

MAC and Not MAC probabilities, Nodes 1 and 2

A mid air collision is defined as a separation when the center of gravities (cg) of two aircraft are 200 feet or less of each other horizontally and 65 feet or less vertically. These distances are a conservative estimate of the volume required to clear most aircraft without structural contact. Very large aircraft such as the Boeing B747-400 (211 feet wingspan), Airbus A380-800 (262 feet wingspan), and Lockheed C5A Galaxy (223 feet wingspan) will require larger volumes. However, for simplification of simulation and analysis, the collision distance is set to the values indicated above.

A critical near mid air collision is defined as an encounter where two aircraft are center of gravity to center of gravity 500 feet or less horizontally and 100 feet or less vertically [4, 9]. See Figure 2.8. A proximity encounter is defined as a distance where two aircraft are one half (½) nautical mile or less horizontally and 500 feet or less vertically.

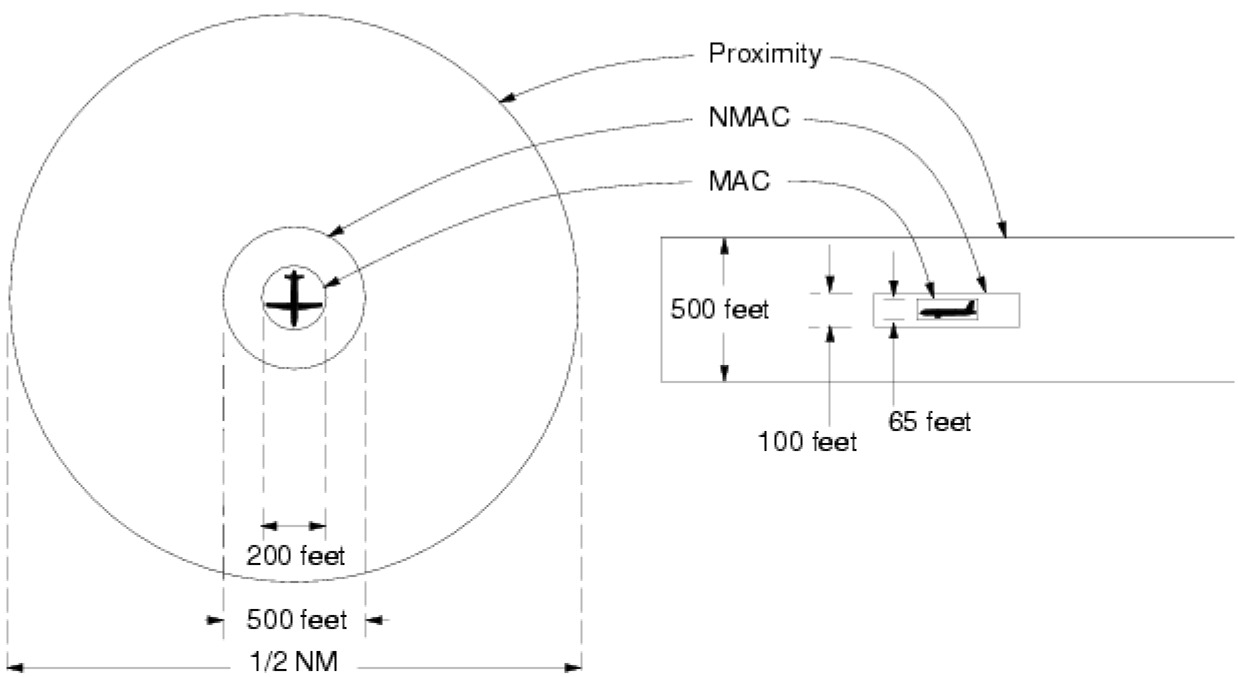


Figure 2.8. Horizontal and Vertical view of MAC, NMAC and Proximity Volumes.

The protected zones for MAC, NMAC and Proximity have been defined such that the diameter (rather than the radius) are 200 feet, 500 feet and ½ NM, respectively. Therefore, an intrusion to these zones is when the protected zones of each aircraft overlap, Figure 2.9.

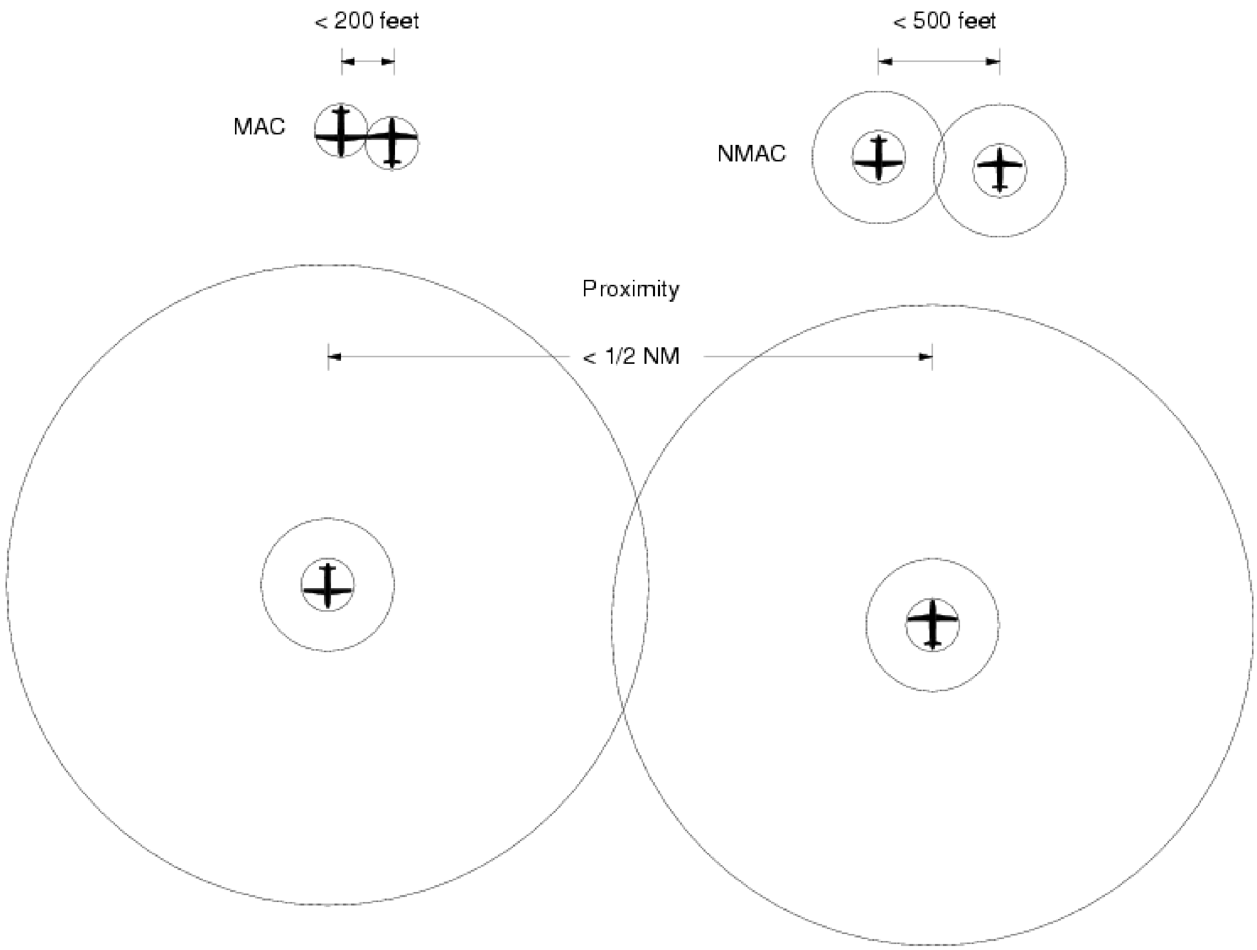


Figure 2.9. Intrusion into Protected Zone for MAC, NMAC, and Proximity.

The probability that two aircraft are in a MAC trajectory given that they are in a Proximity trajectory is based on the definitions above. There are two cases to consider when calculating the probability of collision trajectories. The first is when both aircraft are on level flight. The second is when one or both aircraft are climbing or descending.

The following examples demonstrate how the probabilities are calculated. In Figure 2.10, two aircraft are in a 180 degrees encounter (head on). The location of aircraft 1 along the y axis is assumed to have a uniform distribution. The location of aircraft 1 along the x axis does not affect the closest point of approach distance. The location of aircraft 1 along the z axis (vertical) is also assumed to have a uniform distribution.

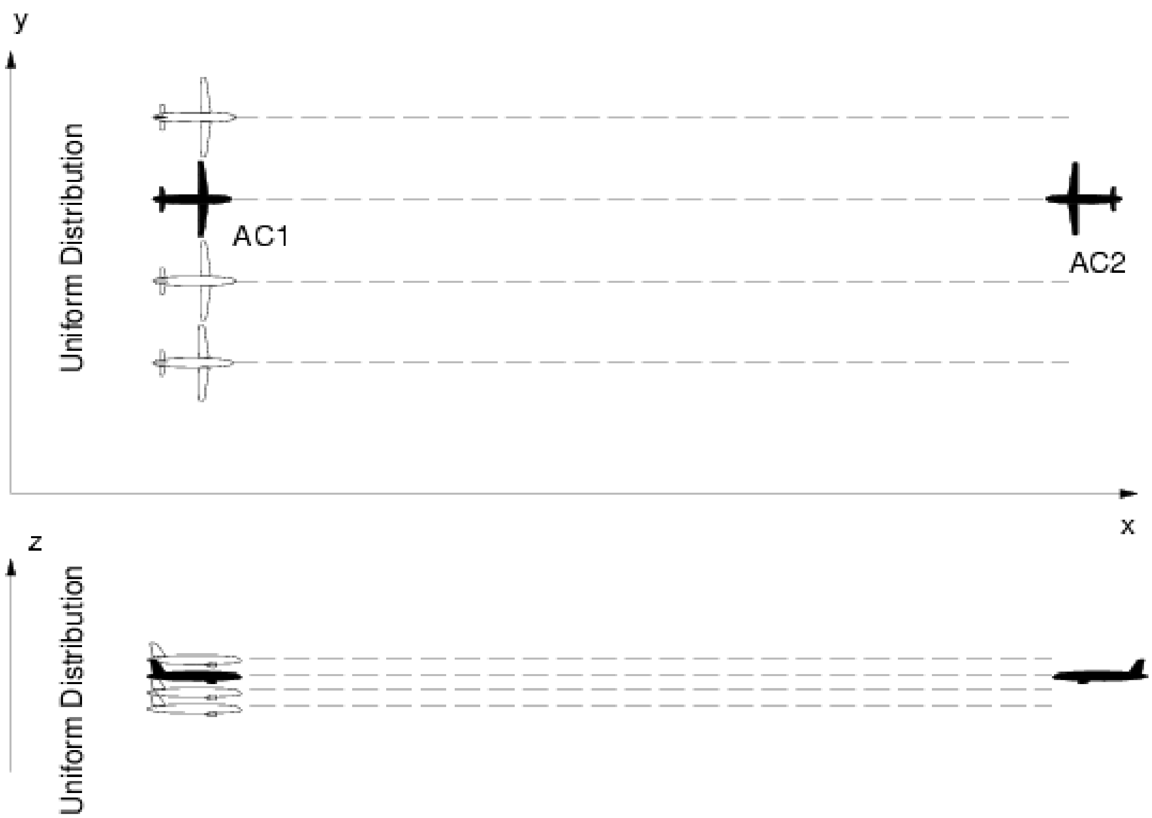


Figure 2.10. Probability of MAC and Proximity Trajectories, Head-on Encounter.

The probability of a collision trajectory given a Proximity trajectory (at level flight), P(ct|pt-level), is the probability that horizontally they are within 200 feet cg to cg, P(cth), times the probability that they are vertically within 65 feet, P(ctv).

P(cth) = 200/3038 = 0.06583

P(ctv) = 65/500 = 0.1300

P(ct|pt-level) = P(ch) x P(cv) = 0.06583 x 0.1300 = 0.008558

Note that this probability is independent of the encounter horizontal angle (crossing angle). Figure 2.11 shows two aircraft with a 135 degrees encounter angle. Without loss of generality, let aircraft 1 and aircraft 2 have vertical speeds equal to 250 knots. Their vectorial speeds are:

vx1 = 250*cos(45) = 176.8 knots
vy1 = 250*cos(45) = 176.8 knots
vx2 = -250 knots
vy2 = 0 knots

The relative speeds and angle of motion of aircraft 1 with respect to aircraft 2 are:

vxr = 426.8 knots
vyr = 176.8 knots
Theta_r = 67.5 degrees

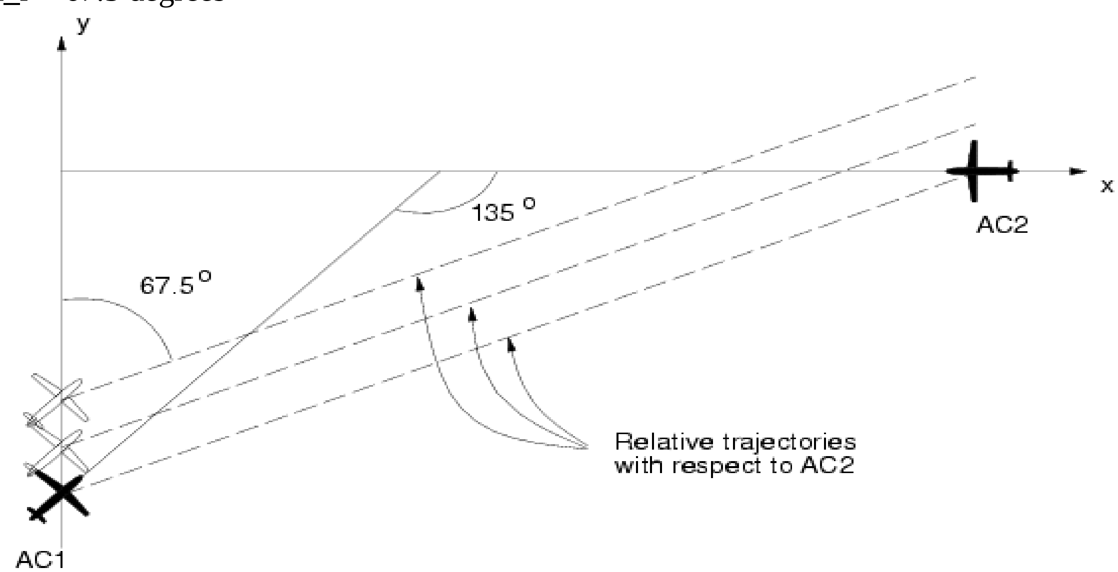


Figure 2.11. Probability of MAC and NMAC Trajectories, 135^{o} Encounter, Showing Closing Relative Horizontal Speed.

A uniform distribution of aircraft 1 over the x and y axes will produce a probability P(cth) of horizontal collision trajectory equal to 0.06583 as before. The probability of vertical collision trajectory is unaffected by the horizontal angle. In general, the relative trajectory of aircraft 1 will tangentially intercept a circle around aircraft 2. The probability of horizontal MAC trajectory given a Proximity trajectory is the ratio of the MAC radius to the Proximity radius.

For encounters where one or both aircraft are climbing or descending, the probability of a collision trajectory given a proximity trajectory is based on the horizontal areas of MAC and Proximity, the vertical area and the relative angle of the aircraft as shown in Figure 2.12. The location of aircraft 1 is assumed to have uniform distributions on the vertical and horizontal axes.

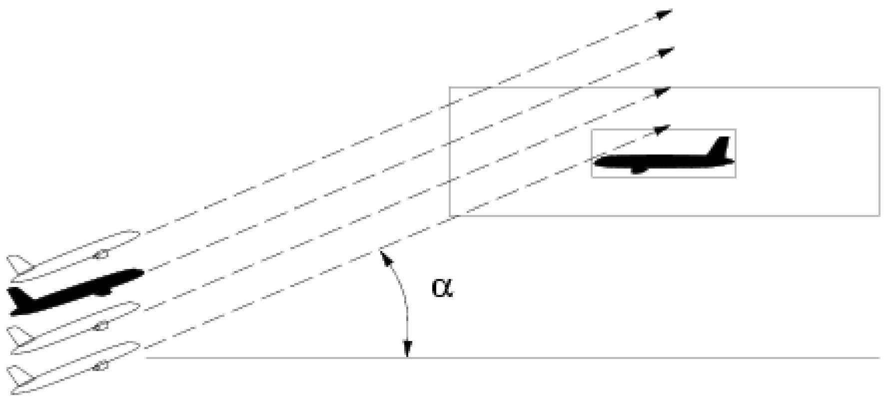


Figure 2.12. Probability of MAC Given Proximity, Climb/Descent.

The horizontal areas of the MAC and Proximity volumes are:

$\text{Area\_h\_}_{MAC} = \pi \ 100^2$ sq feet

$\text{Area\_h\_proc} = \pi \ 1519^2$ sq feet

The vertical area of the MAC and Proximity volumes are:

$\text{Area\_v\_}_{MAC} = 65 \times 200$ sq feet

$\text{Area\_v\_proc} = 500 \times 3038$ sq feet

The probability of MAC trajectory given a Proximity trajectory is:

$$\text{P(ct|nmt-non-level)} = \text{Area}_{MAC}/\text{Area}_{PROC}$$
$$= (\text{Area\_h\_}_{MAC} + \text{Area\_v\_}_{MAC}/\text{Tan}\ \alpha)/(\text{Area\_h\_proc} + \text{Area\_v\_proc}/\text{Tan}\ \alpha)$$

For an aircraft at 250 knots and 500 feet per minute climb, the trajectory angle with respect to the horizon is only 1.13 degrees. This give a probability of MAC trajectory given a Proximity trajectory of:

$$\text{P(ct|nmt-non-level)} = \text{Area}_{MAC}/\text{Area}_{NMAC} = 0.008461$$

The encounter probabilities of Section 3 are used to obtain the probability of level flight encounters and non-level flight encounters. Nineteen encounter classes are presented in Section 3 which were obtained from [4]. For each of these encounters, it is determined if the encounter is a level or non-level flight encounter. Classes 2, 3a, 3b, 7, 8, 9, 10, 12, 13, 17, 18, and 19 are level flight encounters at the closest point of approach. Classes 1a, 1b, 4, 5, 6, 11, 14a, and 14b, 15, 16, are non-level flight encounters at the closest point of approach. The probability of a level flight encounter is:

P(level) = P(class 2) + P(class 3a) + P(class 3b) + P(class 7) + P(class 8) +
P(class 9) + P(class 10) + P(class 11) + P(class 12) + P(class 13) +
P(class 17) + P(class 18) + P(class 19)
= 0.27162

The probability of a non-level flight encounter is:

P(non-level) = P(class 1a) + P(class 1b) + P(class 4) + P(class 5) + P(class 6) +
P(class 11) + P(class 14a) + P(class 14b)
= 0.72837

The probability of a collision trajectory given a proximity trajectory is computed taking into account the probability of encounters:

P(ct|pt) = P(ct|pt-level) x P(level) + P(ct|pt-non-level) x P(non-level)
= 0.008558 x 0.27162 + 0.008461 x 0.72837
= 0.002325 + 0.006163
= 0.008488

Node 1 = 0.008488
Node 2 = 0.991512

2.5.2 Equipment Events

These events result from the behavior of the equipment which is installed on the aircraft for the purpose of collision avoidance.

Sensor does not Detect, Node 28 (unmanned)

Probability that the detection sensor fails to acquire the target traffic. The sensor could be radar, infrared, visual spectrum, transponder query (similar to Mode-S used in TCAS), ADS-B receiver, TIS receiver, other technology, or a combination of sensors. The probability that a Mode-S sensor fails to acquire a target is obtained from reference [1]. The probability that an ADS-B

[redacted]

receiver does not detect an ADS-B equipped aircraft is calculated by the tree in Figure 2.13.

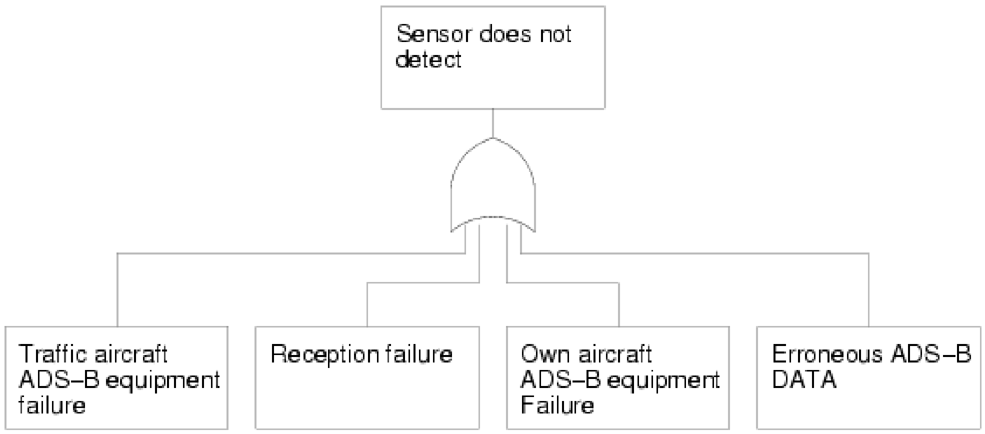


Figure 2.13. Probability of Not Detecting Traffic Aircraft.

Equipment failure probability is based on guidelines of the RTCA DO-242A document [5]. Section 3.3.6.2, *Failure Mode and Availability Considerations*, specify that:

> *Where the ADS-B System is used as a supplemental means of surveillance, the ADS-B system is expected to be available with a probability of at least 0.95 for all operations, independent of the availability of appropriate inputs to the ADS-B system. Where the ADS-B System is used as a primary means of surveillance, the system is expected to be available with a probability of at least 0.999 for all air-air operations.*

Under the assumptions made in this analysis, the unmanned aircraft is operated under ATC services in Class A airspace. The primary means of surveillance is Primary System Radar and Secondary System Radar, PSR/SSR. However, for this analysis, ADS-B is also used for the additional functionality of sense and avoid. It is therefore expected that when used for sense and avoid in addition to supplemental surveillance, a higher availability requirement will be imposed. A value of between 0.99 and 0.999 is assigned to the equipment failure probability.

The probability of reception failure is calculated based on the work of Ronald Staab, reference [12]. Assuming a 20 nautical mile range and 5 FRUIT (False Returns Unsynchronized in Time) the probability of receiving a single message from the traffic aircraft is approximately 0.985. For a 1 second rate of transmission and a 5 second interval, the probability of missing all messages in the 5 second interval is:

Reception Failure = $(1 - 0.985)^5 = 7.59 \times 10^{-10}$

[redacted]

An ADS-B receiver which loses a traffic aircraft messages for longer than 5 seconds will render the accuracy and integrity of that aircraft as invalid, as defined in RTCA DO-260 and DO-260A [14,15]. It should be noted that missing all messages from the traffic for a 5 second interval will not prevent an aircraft from reacquiring the traffic. If the assumption is made that missing to detect a traffic aircraft for more than 5 seconds will significantly compromise the ability to sense and avoid, then this reception failure probability could be used.

An aircraft reporting a location through an ADS-B transmission is expected to be no farther away than a containment radius, Figure 2.14.

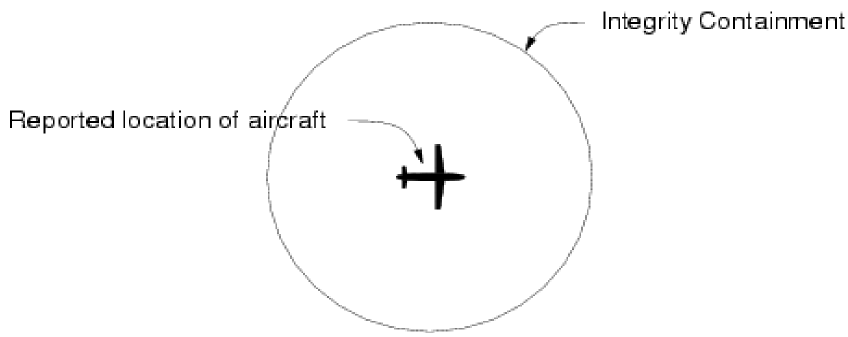


Figure 2.14. Integrity Containment Radius for ADS-B Reported Location.

The Surveillance Integrity Level parameter, SIL, defines how often an aircraft will be outside of this containment radius as measured from the reported location. The values for this parameter are shown in Table 2.1.

SIL	***Probability of Exceeding Containment Radius Reported in NIC without Being Detected***
0	Unknown
1	1 x 10^{-3} per flight hour or per operation
2	1 x 10^{-5} per flight hour or per operation
3	1 x 10^{-7} per flight hour or per operation

Table 2.1. Surveillance Integrity Level, SIL, and Meaning.

Depending on the requirements imposed on the sense and avoid equipment, the probability of undetected erroneous data will be in the range of 1 x 10^{-3} to 1 x 10^{-7} with a corresponding SIL value of 1 to 3. An important factor that is undefined by SIL is the latency of the undetected erroneous data. For example, a SIL of 1 represents that no more than one hour of undetected erroneous data will be transmitted per 1000 flight hours (or operations). However, a continuous one hour of undetected erroneous data followed by 999 hours of good data is much more severe than 1 second of undetected erroneous data followed by 999 seconds of good data. The worst case is assumed in this analysis, where an aircraft could transmit erroneous data exceeding its containment radius for long periods of time but that the ratio of erroneous data time to good data time is in the range 1×10^{-3} to 1×10^{-7}.

Node 28 =

P(Mode-S) = 5.000×10^{-3} from reference [1]

P(ADS-B) = 1.100×10^{-2} to 1.000×10^{-3}

Data Down-Link Fails, Node 29 (unmanned)

The probability that, at the time of the encounter, the data link which sends traffic information from the unmanned aircraft to the control station and the traffic display has failed. The probability is calculated as the amount of flight time with a failed link per flight hour. This probability is affected by the reliability of the equipment and by the operational rules. Given a down-link failure, the aircraft might be allowed to continue in normal flight or an abnormal flight termination might be executed. The probability for this node is based on the hazard analysis conducted by the Reliability Work Package of Access 5. The Hazard Analysis classifies the loss of down link as a minor hazard when an auto-land function is present on the unmanned aircraft and as major hazard when no auto-land function is present. From Advisory Circular AC/AMJ 25.1309 the level of hazard is related to failure probability as shown in Table 2.2.

[redacted]

Effect on Aircraft	***No effect on operational capability of safety***	***Slight reduction in functional capabilities or safety margins***	***Significant reduction in functional capabilities or safety margins***	***Large reduction in functional capabilities or safety margins***	***Normally with hull loss***
Average Probability per flight hour	No requirement	$< 10^{-3}$	$< 10^{-5}$	$< 10^{-7}$	$< 10^{-9}$
Classification of Failure Conditions	No safety Effect	Minor	Major	Hazardous	Catastrophic

Table 2.2. Hazard Severity and Probability of Occurrence.

Based on a minor and major classification, the probability of a down link failure is given the value in the range of 10^{-3} to 10^{-5}.

Node 29 = 1.0×10^{-3} to 1.0×10^{-5}

MFD/ Driver Fails, Node 30

Probability that the traffic data is available at the control station but it is not displayed due to system display failure. This number is based on a single display with a 15 to 40 thousand hours mean time to failure for traffic displays.

Node 30 = 6.666×10^{-5} to 2.500×10^{-5}

2.5.3 Human Factors

These events are the result of the behavior of the pilots and the air traffic controller, if the ATC is involved in the event.

Pilot(s) do not see traffic, Node 3 (manned)

This node is the probability that a pilot or pilots will not see the traffic aircraft. This probability is calculated using a 3 dimensional visual acquisition program described in Section 4.

A pilot might see the traffic aircraft a few seconds before collision. For the purpose of estimating the outcome of the encounter, seeing the aircraft a few seconds before the encounter is equivalent to not seeing it at all as their will not be sufficient time to react. The threshold for calculating whether or not the pilot sees the traffic before collision is set to 5 seconds. Meteorological conditions affect the capacity of a piloted aircraft to see an intruder aircraft. Meteorological conditions will also affect sensing devices such as Lidar, and video surveillance. Visibility and weather conditions are factored in the probability of visual acquisition. Section 3 defines the encounter geometries used to calculate visual acquisition probabilities. Encounter geometries are grouped into Classes and the crossing angles are varied. Table 2.3 gives the probability of the own ship aircraft not seeing the target aircraft as a function of crossing angle for encounter Class 1a. Table 2.4 gives the average probability over the crossing angle range for the 19 class encounters presented is Section 3. The probabilities in the table are calculated for the following parameters:

traffic aircraft: 757-200

true air speed, own: 250 knots

true air speed, traffic: 460 knots

number of pilots, own: 2

climb/descent rates: 500 feet/min

visual range: 20 nautical miles

tau 2: time to collision: 5 seconds

Crossing Angle, degrees	***Probability No Visual***	***Crossing Angle, degrees***	***Probability No Visual***	***Crossing Angle, degrees***	***Probability No Visual***
0	1.0000	65	0.0000	130	0.0744
5	1.0000	70	0.0000	135	0.1000
10	1.0000	75	0.0001	140	0.1313
15	1.0000	80	0.0003	145	0.1690
20	1.0000	85	0.0007	150	0.2142
25	1.0000	90	0.0016	155	0.2666
30	1.0000	95	0.0032	160	0.2897
35	0.0000	100	0.0059	165	0.3129
40	0.0000	105	0.0102	170	0.3363
45	0.0000	110	0.0166	175	0.3600
50	0.0000	115	0.0256	180	0.3839
55	0.0000	120	0.0378		
60	0.0000	125	0.0539		

Table 2.3. Probability of No Visual Acquisition as Function of Crossing Angle.

Crossing angles between 0 and 30 degrees give a probability of one because the ownship is unable to see the intruder aircraft given the field of regard from the cockpit and the geometry of the encounter. For angles between 35 and 70 degrees, the ownship is able to see the intruder out of the window and due to the geometry, the closing speeds are relatively slow, given ample opportunity for a pilot who is scanning the horizon to see the intruder. As the encounter becomes more a head-on encounter, for angles 75 to 180 degrees, the closing speeds become greater, making it more difficult to see the aircraft tau seconds before collision.

Class	***Average Probability*** ***No visual***	***Class***	***Average Probability*** ***No visual***	***Class***	***Average Probability*** ***No visual***
1a	0.2640	6	0.2606	13	0.2610
1b	0.2612	7	0.2661	14a	0.2619
2	0.2661	8	0.2610	14b	0.2619
3a	0.2610	9	0.2597	15	0.2626
3b	0.2610	10	0.2661	16	0.2624
4	0.2606	11	0.2626	17	0.2661
5	0.2626	12	0.2661	18	0.2610
				19	0.2597

Table 2.4. Average Probability of Ownship not Seeing Traffic.

Based on a weighed average, taking into account the frequency of the encounters (see Table 3.1), the probability is set to:

Node 3 = 0.2630

Traffic not Perceived as Threat, Node 5 (manned)

This node represents the probability that a pilot sees a traffic aircraft which is in a collision course or near collision course but does not think the traffic is a threat and does not take any evasive action. This number is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 5 = 1×10^{-2} to 1×10^{-3}

Late or no Maneuver, Node 7 (manned)

Probability that a pilot sees the traffic as a threat but either cannot determine an evasive maneuver, takes too long to determine a maneuver leaving insufficient time to execute, or initiates the maneuver late. In the case where a CAS is on-board, this node also reflects the probability that the CAS logic issues a resolution advisory (RA), but the pilot does not execute the advisory or executes late. (Note that for the analysis presented in this document, it is assumed that no CAS logic exist on-board the manned aircraft.) This number is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 7 = 1×10^{-1} to 1×10^{-2}

Executed Incorrectly, Node 8 (manned)

Pilot determines a maneuver which will provide avoidance, but the execution does not follow the intended maneuver. This could be the result of insufficient yoke force, incorrect bank angle to accomplish the intended turn rate, incorrect thrust setting for the maneuver, etc. This number is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 8 = 1×10^{-2} to 1×10^{-6}

Pilot(s) Determine Resolution, Node 10 (manned)

When there is a collision avoidance system (CAS) on-board, the pilot will have the option of following the resolution advisory, RA, issued by the CAS or determining his own resolution maneuver. It is possible that the pilot determines that a resolution maneuver is necessary but the CAS logic does not issue an RA. It is also possible that the CAS issues an RA but the pilot determines that no maneuver is needed. The calculation for the baseline in this document is made without CAS. Therefore, the pilot will be determining all resolutions and this node is set to 1.

Pilot(s) see traffic, Node 14 (manned)

Complement probability to Node 3. The Subtree B estimates the probability that given two aircraft are not in a collision course, the avoidance maneuver causes a collision. For this to occur, the traffic must have been detected.

Traffic identified as requiring avoidance, Node 15 (manned)

Given that separation minima will be violated and the two aircraft are in a proximity trajectory course, the aircraft crew or the CAS logic could identify the traffic aircraft as a collision threat and determine an avoidance maneuver. This number is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 15 = 1×10^{-2} to 1×10^{-5}

Pilot(s) Maneuver, Node 16 (manned)
This node estimates the probability that the pilot maneuvers after identifying the traffic as a threat and determining a resolution maneuver or receiving a resolution advisory from the CAS logic if aircraft is equipped with CAS. This node is associated with Node 7 and is the complement of the probability that the pilot will not maneuver.

Pilot(s) Determine Resolution, Node 17 (manned)
The calculation for the baseline in this document is made without CAS. Therefore, the pilot will be determining all resolutions and this node is set to 1. See Node 10.

Proximity Trajectory, Node 21
The probability of a proximity trajectory is the probability that two aircraft in their current course will lose separation as defined in section 1.2. Node 21 is the probability that 2 aircraft are in a loss of separation course or in a collision course. For Node 21 probability, a proximity trajectory includes a MAC trajectory. The trajectory is considered a proximity trajectory if the two aircraft are less than 120 seconds to closest point of approach, CPA. That is, if no action is taken by either aircraft, the aircraft will experience a loss of separation or a MAC in less than 120 seconds. The time constraint is due to ATC automation. Typically, ATC centers have collision avoidance logic which will warn controllers of an impeding loss of separation 120 seconds before closest point of approach. Therefore, for a proximity course less than 120 seconds to CPA, it is assumed that ATC and procedures will not be a contributing factor to collision avoidance.
To compare the ability of a piloted aircraft to avoid a collision with the ability of an unmanned aircraft to avoid a collision, the value of node 21 is set to 1. That is, procedures in the NAS and ATC services will be factored out for the comparison. In setting this probability to 1, there is an implicit assumption that a manned aircraft and an unmanned aircraft have the same probability of being in a proximity trajectory. This assumption is not necessarily valid because manned aircraft and unmanned aircraft have nominally different missions and flight profiles. To calculate the overall collision probability of manned and unmanned aircraft, the probability of a proximity trajectory will be revised as more knowledge is gained about the operations of unmanned aircraft.

Pilot does not See Traffic, Node 22 (unmanned)
Probability that a remote pilot does not scan the traffic display of the control station and does not see the traffic aircraft before a collision. This probability, in contrast to the manned aircraft, is not affected by visual acuity, size of the traffic aircraft, encounter geometry, and weather conditions. It is affected by work load, attentiveness, training, type of display, and other factors. There is very limited or no data available for remotely operated aircraft on collision trajectories.

In a civilian airspace environment under positive air traffic control, an aircraft will fly ten of thousands of hours without experiencing a proximity trajectory undetected by ATC and even more rarely an undetected collision trajectory. The probability assigned to this node is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 22 = 1.0×10^{-2} to 1.0×10^{-4}

Late or no Maneuver, Node 24 (unmanned)

Probability that a pilot sees the traffic as a threat but either cannot determine an evasive maneuver, takes too long to determine a maneuver leaving insufficient time to execute, or initiates the maneuver late. In the case where a CAS is at the control station, this node also reflects the probability that the CAS logic issues a resolution advisory (RA), but the pilot does not execute the advisory or executes late. Reference [1] estimates the probability of a slow response to a TCAS RA in the 0.5444 to 0.680 range. However, for this node, a late maneuver does not mean a slow reaction but rather sufficiently late that the maneuver is ineffective to avoid the collision. The probability assigned to this node is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 24 = 1.0×10^{-1} to 1×10^{-3}

Executed Incorrectly, Node 25 (unmanned)

Pilot determines a maneuver or receives a resolution advisory which will provide avoidance. However, the execution does not follow the intended maneuver. The probability is obtained from reference [1]. Reference [1] provides a probability that given an ACAS (TCAS) vertical resolution advisory, the pilot execute the resolution in the wrong direction. That is, if the resolution is to climb, the pilot descends and if it is to descend, the pilot climbs.

Node 25 = 8.0×10^{-2} to 1.0×10^{-3}

Traffic not Perceived as Threat, Node 26 (unmanned)

Probability that a pilot sees a traffic aircraft which is in a collision course or near a collision course but does not think the traffic is a threat. This probability does not include any type of warning from a CAS logic. It is the probability that by looking at a symbol on a screen, the apparent motion of the symbol on the screen, and the altitude and rate of change of altitude of the traffic, the pilot can identify the traffic as a threat. The type and design of the display will have a significant impact in this probability. For example, a horizontal (view from the top) display will make easier to detect traffic at co-altitude approaching from a given bearing. A traffic aircraft at closely the same horizontal location as the ownship and threatening the ownship by climbing or descending will be very difficult to detect as the ownship and traffic aircraft symbols will overlap. The altitude must be read from the numerical value of the symbol, Figure 2.15.

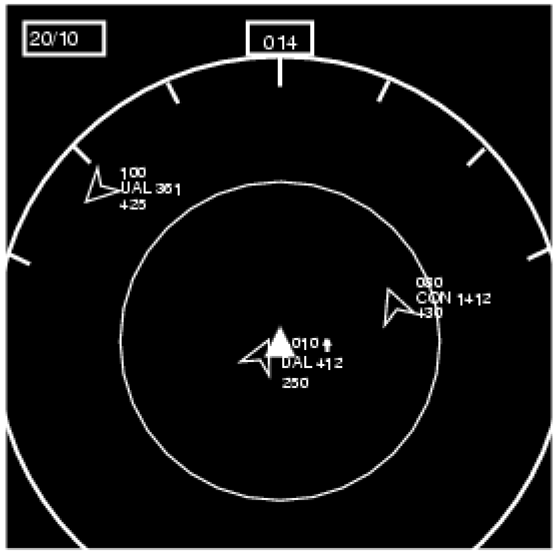


Figure 2.15. Example of Traffic Display.

The probability assigned to this node is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 26 = 1.0×10^{-2} to 1.0×10^{-3}

Pilot Determines Resolution, Node 31 (unmanned)

This is the probability that the pilot determines an evasive maneuver given that there is no Resolution Advisory from the CAS logic or that the pilot ignores the RA and follows his own evasive maneuver. Whether or not a pilot decides to follow the CAS logic RA or perform his own avoidance maneuver depends on operational guidelines, training and other human factors. This node is the complement to Node 33.

Node 31 = 1 – Node 33.

2.5.4 Logic Events

logic events refer to the alerts and resolution maneuvers that the CAS, the pilot or the controller (if a controller is involved) derive based on the data or the perception of the situation.

CAS Does not Warn, Node 4 (manned)
This node is in the tree for completness and future analysis. The probability of collision for the baseline manned aircraft is computed without an on-board collision avoidance system (CAS). This node value is set to 1.

CAS Logic Does not Warn, Node 6 (manned)
This node is in the tree for completeness and future analysis. The probability of collision for the baseline manned aircraft is computed without an on-board collision avoidance system (CAS). This node value is set to 1.

Resolution Incorrect, Node 11 (manned)
Probability that a pilot-generated resolution maneuver fails to avoid the collision. This could be the result of an incorrect assessment of the encounter or that the traffic maneuvers in a way that negates the avoidance maneuver of the ownship. Rules of the road as defined in the Federal Aviation Regulations, 14 CFR Part 91.113 will lessen the chances of two aircraft maneuvering into each other. The probability assigned to this node is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 11 = 1.0×10^{-1} to 1.0×10^{-3}

CAS Logic Issues RA/ Pilot Selects, Node 12 (manned)
This node is in the tree for completeness and future analysis. The probability of collision for the baseline manned aircraft is computed without an on-board collision avoidance system. This node value is set to 0.

RA Incorrect, Node 13
Probability that if there is a collision avoidance system on-board, the resolution generated by the CAS logic fails to solve the collision. This node is in the tree for completeness and future analysis. The probability of collision for the baseline manned aircraft is computed without an on-board collision avoidance system. This node value is set to 0.

Resolution is MAC Trajectory, Node 18 (manned)
Probability that the resolution maneuver determined by the pilot reduces the separation at the closest point of approach causing a collision where the original trajectories were not collision trajectories. This probability is dependent on the size of the proximity trajectory. The larger the proximity trajectory, the lower the probability that an aircraft will maneuver into the traffic. The probability for this node is estimated for the proximity trajectory as defined in Section 1.5. Assuming a purely random maneuver, a geometric analysis similar to that for Nodes 1 and 2 can be performed. This yields a probability in the order of 0.005 of collision. If the pilots follow the

rules of the rode, the probability of maneuvering towards the traffic should be significantly reduced.

Node 18 = 5.0×10^{-3} to 1.0×10^{-5}

CAS Logic Issues RA/Pilot Selects, Node 19 (manned)

This node is in the tree for completeness and future analysis. The probability of collision for the baseline manned aircraft is computed without an on-board collision avoidance system. This node value is set to 0.

RA is MAC trajectory, Node 20 (manned)

Probability that resolution advisory maneuver reduces the separation at the closest point of approach causing a collision where the original trajectories were not collision trajectories. This node is set to 0 based on the assumption that CAS is not present.

CAS Logic Does not Warn of Traffic Presence, Node 23 (unmanned)

If the unmanned aircraft's control station is equipped with collision avoidance system, this is the probability that the CAS does not alert the pilot of the presence of traffic. This probability is highly dependent on the system design. It could be possible that it is undesirable to have a traffic presence warning as this might cause excessive alerts which lead to pilots disregarding warnings. A traffic presence warning could also be user selectable and/or sensitivity adjustable with regard to horizontal and vertical distance. In higher density conditions, sensitivity could be reduced to avoid excessive alerts. The probability assigned to this node is based on discussions with system designers, pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 23 = 1.0 to 1.0×10^{-6}

CAS Logic Does not Warn of Collision Trajectory, Node 27 (unmanned)

If the unmanned aircraft's control station is equipped with collision avoidance system, this is the probability that based on the data supplied to the CAS logic, the logic does not warn the pilot of an impending collision. This probability is based on simulations of conflict and collision avoidance logic. The distinction between conflict and collision avoidance is determined by the time length of the look ahead time and the horizontal and vertical separation objectives. Conflict avoidance involves look ahead times in the order of 5 minutes to several hours and horizontal and vertical separation of 5 NM and 1000 feet, respectively. Collision avoidance deals with look ahead times in the order of 20 seconds to a few minutes and horizontal and vertical separations of less than 0.5 NM and 500 feet respectively. Reference [10] shows that, given accurate surveillance data, the conflict detection logic was successful in detecting all conflicts in more than 3.3×10^{5} encounters. Reference [11] shows results of conflict and collision avoidance experiments for a terminal or merging area environment in which all conflicts/collision trajectory were detected for more than 300 operations. The case for erroneous or non-existent data is not considered by this node and is included in node 28. Based on the simulation experiments, a probability is assigned for CAS logic not warning of collision trajectory.

Node 27 = 3.03×10^{-6}

Resolution Incorrect, Node 32 (unmanned)

Probability that a pilot-generated resolution maneuver fails to avoid the collision. The maneuver is generated by observing the control station traffic display and determining a suitable maneuver to avoid the collision. The probability assigned to this node is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 32 = 0.2 to 0.1

CAS Logic Issues RA, Node 33 (unmanned)

Probability that the CAS logic issues an RA and that the pilot decides to follow the CAS logic RA and does not follow his own resolution maneuver. The CAS logic probability follows from the same simulation experiments as Node 27. Whether or not a pilot decides to follow the CAS logic RA or perform another avoidance maneuver depends on operational guidelines, training and other human factors. The probability that the logic issues an RA is expected to be greater than 3.3×10^{5}. Of 170 TCAS reported incidents in reference [13], 8% of pilots chose to ignore the RA advisory and maneuver based on their own judgment. However, this data is for manned aircraft with visual capabilities. It is expected that a remote pilot using a traffic display will be more incline to follow the RA. The probability that the pilot follows the logic is the dominant factor for this node.

Node 33 = 0.92 to 0.999

RA incorrect, Node 34 (unmanned)

Probability that the resolution maneuver issued by the CAS logic fails to avoid the collision. In collision avoidance logic, the resolution calculation is based on projecting the state and velocity vectors of the intruder aircraft and determining a change in velocity vector of the own ship to achieve the required avoidance. When the traffic aircraft alters its course, the resolution generated by the ownship to avoid the collision might no longer achieve its objective. This is the main reason why an RA fails to avoid the collision. Other less influential factors that might make the RA fail include aircraft performance, proximity to terrain, high density traffic environment, surveillance data error, etc. From reference [1], the probability that a TCAS generated RA fails to resolve a collision is estimated to be 9.209 x 10^{-2} to 8.873 x 10^{-2} and the probability used for this node.

Node 34 = 9.209 x 10^{-2} to 8.873 x 10^{-2}

Pilot detects traffic, Node 35 (unmanned)

This node is the complement to traffic not detected. Traffic is not detected if not on display or the remote pilot fails to see it on the display.

Traffic identified as requiring avoidance, Node 36 (unmanned)

Given that separation minima will be lost and the two aircraft are in a proximity trajectory course, the aircraft crew or the CAS logic could identified the traffic aircraft as a collision threat and determine an avoidance maneuver. This number is based on discussions with pilots and aeronautical experts and is not based on any experimentation, analysis or simulation.

Node 15 = 1 x 10^{-2} to 1 x 10^{-5}

Pilot(s) Maneuver, Node 37 (unmanned)

This node estimates the probability that the pilot maneuvers after identifying the traffic as a threat and determining a resolution maneuver or receiving a resolution advisory from the CAS logic. This node is associated with Node 24 and is the complement of the probability that the pilot will not maneuver.

Mode 37 = 1 – Node 24

Pilot Determines Resolution, Node 38 (unmanned)

This node is the complement to Node 40.

Node 38 = 1 – Node 40

Pilot resolution is MAC Trajectory, Node 39 (unmanned)

Probability that the resolution maneuver determined by the pilot reduces the separation at the closest point of approach causing a collision where the original trajectories where not collision trajectories. This probability is dependent on the size of the proximity trajectory. The larger the proximity trajectory, the lower the probability that an aircraft will maneuver into the traffic. The probability for this node is estimated for the proximity trajectory as defined in Section 1.5. Assuming a purely random maneuver, a geometric analysis similar to that for Nodes 1 and 2 can be performed. This yields a probability in the order of 0.005 of collision. If the pilots follow the rules of the rode, the probability of maneuvering towards the traffic should be significantly reduced.

Node 18 = 5.0×10^{-3} to 1.0×10^{-5}

CAS Logic Issues RA, Node 40 (unmanned)
Probability that the CAS logic issues and RA and that the pilot decides to follow the CAS logic RA and does not follow his own resolution maneuver. The probability that the CAS issues an RA is lower than for Node 33 because the aircraft are in a proximity trajectory and not in a collision trajectory. Whether or not the logic issues the RA depends on the sensitivity of the logic and the trade off between false alerts and untimely alerts. The dominant factor in this probability, however, is the pilots willingness to follow the RA. This probability is estimated from [13].

Node 33 = 0.92 to 0.999

RA is MAC trajectory, Node 41 (unmanned)
Probability that the RA issued by the CAS logic will induce a collision when the aircraft are not in a collision course. This probability is estimated from geometrical considerations and from reference [1].

Node 41 = 5.68×10^{-4} to 1×10^{-5}

3. Encounter Geometries

The encounter geometries presented in this section are the encounters used in the TCAS II safety analysis [4]. The encounters are divided into 19 classes. These encounters were obtained from terminal area radar observations in the mid 1980s. The subset of encounters used were encounters considered to have generated an RA by a TCAS unit. Each encounter class is given a probability of occurrence associated with the frequency of observation. The encounter classification is based on the vertical speed of the aircraft before and after the closest point of approach, CPA. For example, given aircraft A and B in the encounter, Class 1 defines the encounter in which aircraft A is (changing altitude) before the CPA, aircraft A is changing altitude after the CPA, and aircraft B is in level flight before and after the CPA.
In this report, the Classes 1, 3, and 14 are subdivided into Classes 1a, 1b, 3a, 3b, 14a, and 14b. The subdivision of the encounters into *a* and *b* makes a distinction on whether changing altitude

is a climb or a descent. The distinction is made because it is expected that the ownship will have different visual acquisition rates for an intruder that is climbing as opposed to an intruder that is descending.

The encounter geometry data does not contain crossing angle information. The crossing angle is the angle formed by the aircraft's paths as observed from above. That is, the crossing angle is the difference in bearing of the two aircraft. See Figure 3.23. For the calculation of visual acquisition probabilities, a uniform distribution is assumed for the crossing angle.

The data used for the encounter geometries is based on terminal area radar observation of manned aircraft. These data might not be representative of en-route encounters and unmanned aircraft flight profiles. As more knowledge is gained about unmanned aircraft operations, these data will be revised.

The encounter classes are represented in the vertical plane in Figures 3.1 to 3.22.

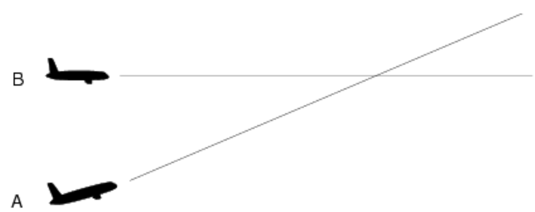


Figure 3.1. Class 1a

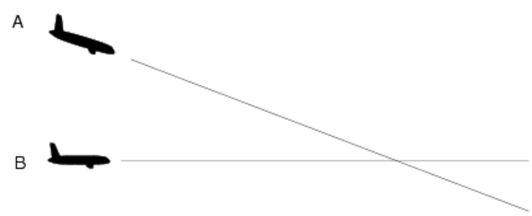


Figure 3.2. Class 1b

Figure 3.3. Class 2.

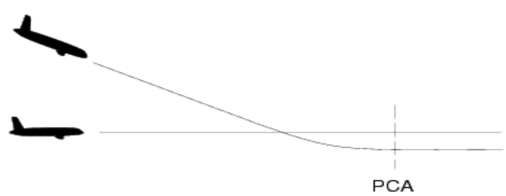
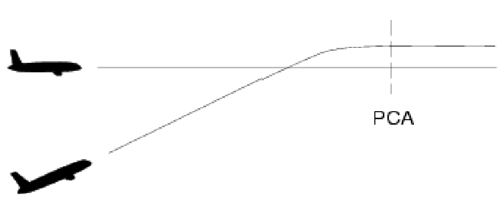
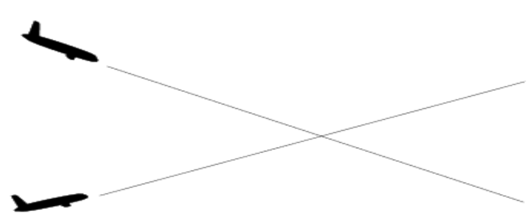


Figure 3.4. Class 3a.





[redacted] [redacted]

Figure 3.5. Class 3b.

Figure 3.6. Class 4.

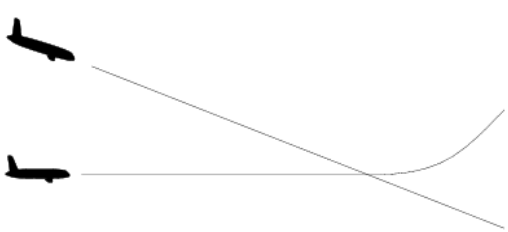


Figure 3.7. Class 5.

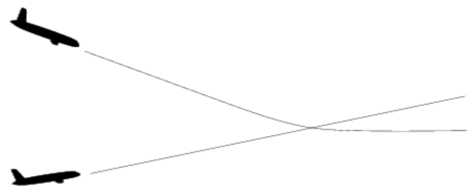


Figure 3.8. Class 6.

Figure 3.9, Class 7.

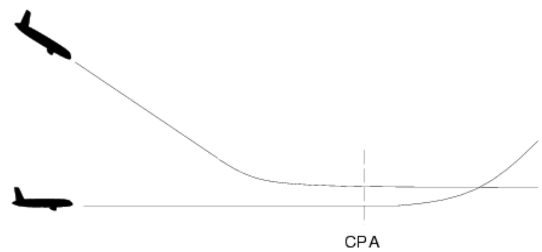


Figure 3.10. Class 8.

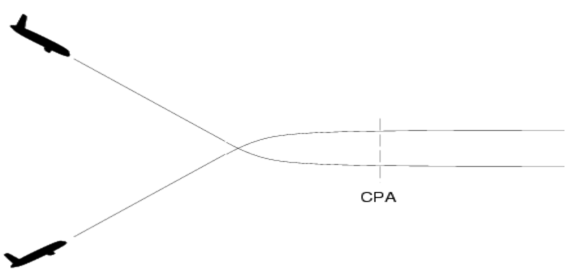


Figure 3.11. Class 9.

Figure 3.12. Class 10.

[redacted] [redacted]

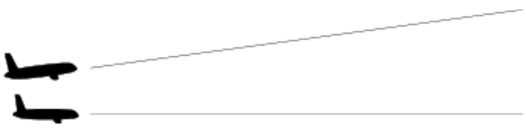


Figure 3.13. Class 11.

Figure 3.14. Class 12.

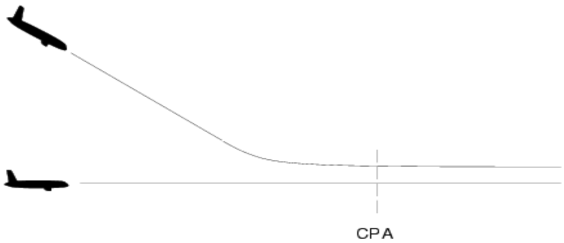


Figure 3.15. Class 13.

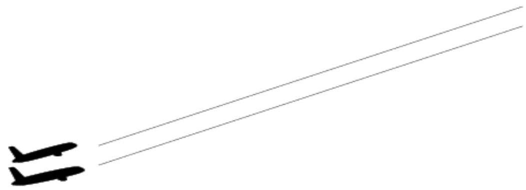


Figure 3.16. Class 14a.

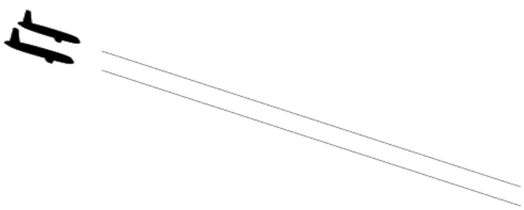


Figure 3.17. Class 14b.

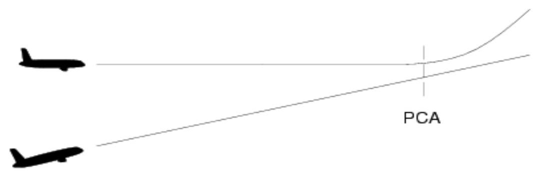


Figure 3.18. Class 15.

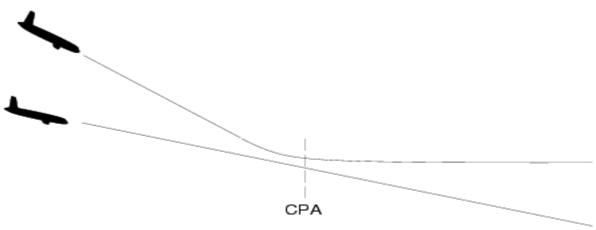


Figure 3.19. Class 16.

Figure 3.20. Class 17.

[redacted] [redacted]

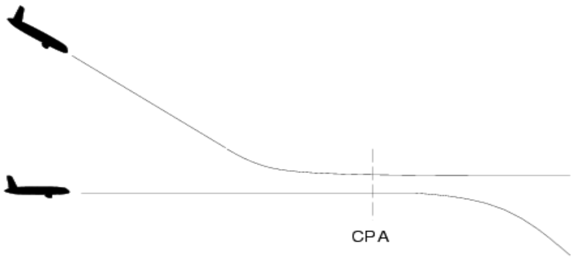


Figure 3.21. Class 18.

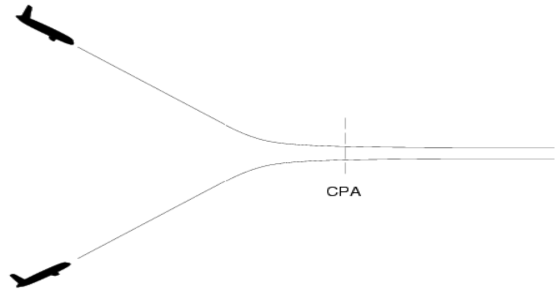


Figure 3.22. Class 19.

The encounter classes are not all likely to occur with the same frequency. The probability of occurrence given to each of the encounter class in reference [4] is shown in Table 3.1.

Class	*P Occurrence*	*Class*	*P Occurrence*	*Class*	*P Occurrence*
1	0.01733	7	0.00002	13	0.07914
2	0.00092	8	0.00002	14	0.05960
3	0.00046	9	0.00002	15	0.01406
4	0.01205	10	0.17004	16	0.04914
5	0.00046	11	0.57531	17	0.00008
6	0.00042	12	0.01574	18	0.00510
				19	0.00008

Table 3.1. Probability of Occurrence.

For each of the class encounter geometry, the encounter crossing angle is varied from 0 to 180 degrees in 5 degrees increments. The top view of the encounters is show in Figure 3.23.

[redacted]

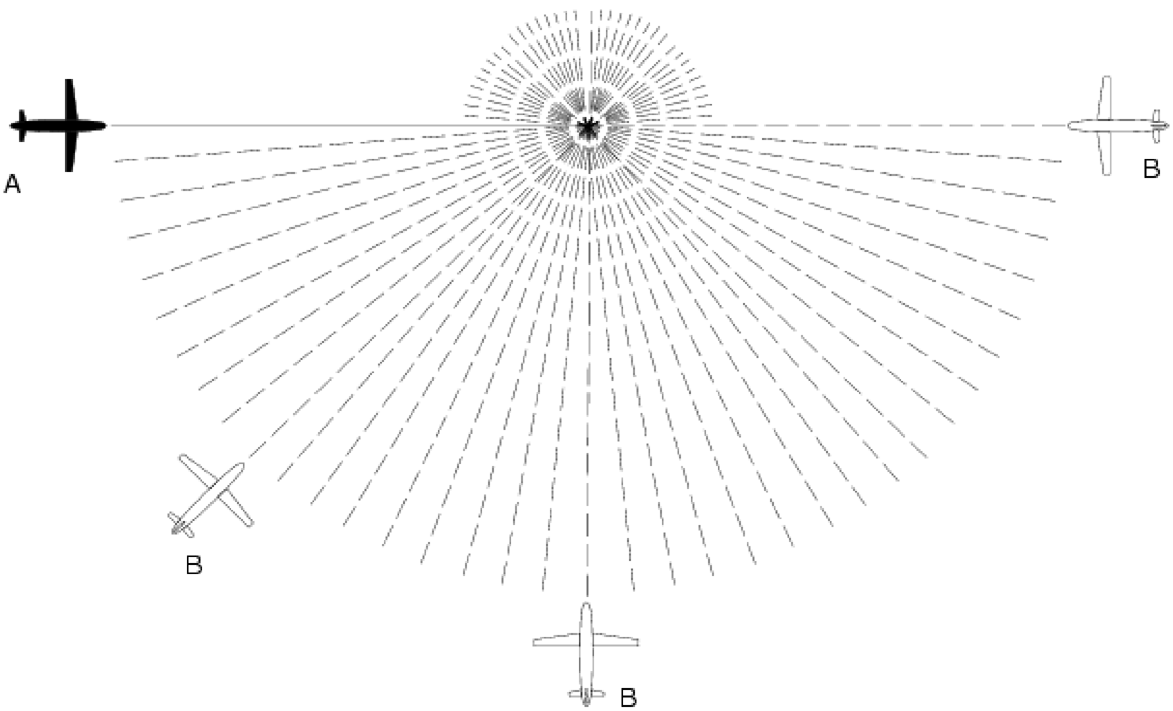


Figure 3.23. Top view of Encounter Geometries Showing Crossing Angle.

The probabilities for the tree nodes are computed for 37 crossing angles for each encounter class. The average probability of collision for the 37 angles is computed and used for the class node on the event tree.

Descend and climb rates are set to 500 feet per minute for constant climbs or descents. Descend and climb rates are set to 1000 feet per minute when the aircraft goes from level flight to altitude change or from altitude change to level flight. For encounter classes 3a, 3b and 9, the aircraft are climbing or descending to a point 20 seconds before CPA and leveling off for the segment 20 to T_{visual} seconds before CPA.

4. Visual 3D Visual Acquisition Program

The visual 3D program was developed to calculate the probability that a pilot or pilots can see a traffic aircraft during encounters in which the vertical velocity of the intruder or ownship might not be zero. That is, one or both aircraft might be climbing or descending. This program is a three dimensional extension of the two dimensional SEE1 program reported in [2]. It is written in Java and can be executed in various computer platforms. The program calculates the probability that a pilot or pilots will be able to visually detect a target aircraft *t* seconds before the CPA. The program takes 20 inputs and outputs the acquisition probability. The inputs to the program are:

Type of aircraft, traffic	True air speed, own	True air speed, traffic

[redacted] [redacted]

Crossing angle
Climb rate, own
Climb rate, traffic
Visual range
Resolution limit
Field of view, H up
Field of view, H down
Field of view, left
Filed of view, right
Search, pilot 1
Search, pilot 2
Beta 0, search effectiveness
Beta 1, search effectiveness
Tau 1, beta transition, time
Tau 2, Pacq, time
D1, beta transition, range
D2, Pacq, range

Default values for these parameters are:

Visual range: 20 nautical miles
Resolution limit: 1 arc-min
Field of view, H up: 60 degrees
Field of view, H down: -75 degrees
Field of view, left: -120 degrees
Field of view, right 90 degrees
Search pilot 1: 1 (pilot present)
Search pilot 2: 1 (pilot present)
Beta 0: 17000 steradian-sec
Beta 1: 17000 steradian-sec
Tau 1: 180 seconds
Tau 2: 12 seconds

Figure 4.1 shows a 3-dimensional representation of an encounter with the parameters used by the Visual 3D program.

[redacted]

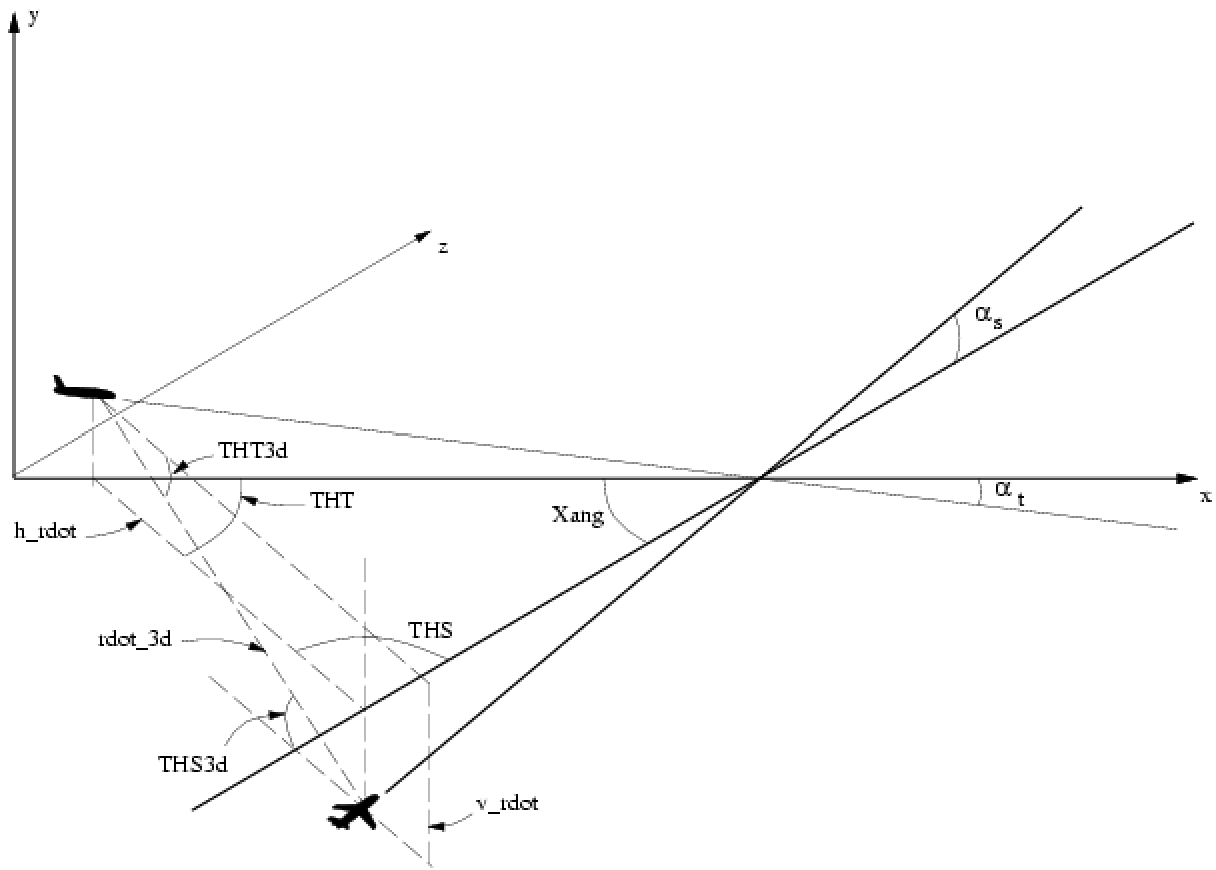


Figure 4.1. Three Dimensional Encounter as Constructed by the Visual 3D Program.

These parameters are derived from the inputs given to the program and include rate of change of aircraft range and angles of view.
The program calculates the probability of visual acquisition for linear trajectories. Trajectories that change vertical speeds and/or are not linear horizontally are approximated by segments of linear trajectories. The program does not provide for night time visual acquisition calculations.

5. Summary and Conclusion

The event trees presented in this paper are a framework to calculate the probability of collision for manned aircraft and for unmanned aircraft. The top level tree, Figure 2.3, is common to both trees. Subtrees A and B have nodes that are more specific to manned and unmanned flight operations. The trees can be used to calculate an absolute probability as well as a risk ratio. A risk ratio calculation or relative probability has two main advantages:

1.By changing only parts of an event tree for the comparison, errors in estimating basic events affecting both trees are factored out. The effort of the analysis can be focused on the differences between the trees, which are the more critical factors.

2.Comparing the tree of interest to a well understood and established tree add credibility and accuracy to the calculation. When a comparison is made between a unmanned collision tree and a manned collision tree, the manned collision tree can be checked against actual data to make sure that the tree's absolute value is accurate. Historical data of collision between manned aircraft can be obtained from the National Transportation Safety Board. This process will be similar to calibrating the tree that is used as the reference. However, the collision between aircraft flying in Class A airspace (FL180 and above) is extremely rare and presents some statistical challenges.

Using the values assigned to the nodes in Section 2.5, the following risk ratio table is calculated. The Risk Ratio is the probability of collision of a unmanned aerial system divided by the probability of collision of a manned aircraft using only see and avoid under VMC (Visual Meteorological Conditions) with no collision avoidance system on-board. The upper bound is the probability calculated using the numbers in the range (Section 2.5) that gives the worst outcome. The lower bound is calculated using the numbers is Section 2.5 for the best collision probability.

Risk Ratio		***See and Avoid, Manned***	
		Probability of collision Upper bound	Probability of collision Lower bound
Sense and Avoid UAS (Unmanned)	Probability of collision Upper bound	0.5846	0.9666
	Probability of collision Lower bound	0.1938	0.3203

Table 5.1. Risk Ratio of Sense and Avoid vs. See and Avoid.

When calculating the probability of collision for a manned aircraft, the dominant factor is the visual acquisition probability. In a clear day with 20 NM visibility and the other factors described in Section 2.5.3, a pilot has approximately a 25% probability of not seen a traffic aircraft in a collision course.

A remotely piloted unmanned aircraft has a much higher probability of detecting a traffic aircraft in a collision course. This was based on Mode-S surveillance or ADS-B following RTCA-DO-

260 or 260A requirements. The dominant factor affecting the probability of collision for a remotely piloted UAS is implementing the avoidance maneuver.

The risk ratio calculations suggest that an UAS can achieve a comparable level of safety to see and avoid. It is important to note, however, that some of the values assigned to the nodes are based on opinions from pilots and aeronautical experts. More extensive analysis and simulation is required to validate the node probabilities. Also noteworthy is that these probabilities are for the ownship avoiding the traffic. It does not take into account the probability that the traffic aircraft will see/sense the ownship and avoids it in cases that the ownship fails to see/sense the traffic.

The risk ratio calculations have been made for a manned aircraft with two pilots and without collision avoidance equipment on-board. The event trees and analysis structure, however, are built such that the calculations can be made for a maned aircraft with a collision avoidance system on-board such as TCAS. These calculations could be performed in future work.

6. Acronyms

ACAS – Airborne Collision Avoidance System
CAS – Collision Avoidance System
CCA – Cooperative Collision Avoidance
CI – Controller Instruction
CPA – Closest Point of Approach
ELOS – Equivalent Level of Safety
FL – Flight Level; FL400 = 40,000 feet
MAC – Mid-Air Collision
NAS – National Airspace System
NASA – National Aeronautic and Space Administration
NMAC – Near Mid-Air Collision
RA – Resolution Advisory
ROA – Remotely Operated Aircraft
RVSM – Reduced Vertical Separation Minima
TCAS – Traffic and Collision Avoidance System
UAS – Unmanned Aircraft System

7. Bibliography

[1] ACAS Programme, ACAS Project, Work Package 1; Final Report on Studies on the Safety of ACAS II in Europe, ACASA/WP-1.8/210D, Version 1.3, March 2002, pages 119.

[redacted]

[2] Richard Theokas; Effect of ADS-B on Near Mid-air Collision Rates of GA Aircraft, presentation, May 2004.

[3] Leo Wapelhorst, John Van Dongen; Test Results of Initial Installation of DATAS/TCAS Monitor – DFW Airport, DOT/FAA/CT-TN91/56, January 1992, pages 61.

[4] Michael McLaughlin, Safety Study of the Traffic Alert and Collision Avoidance System (TCAS II), MITRE Technical Report MTR 97W0000032, June 1997.

[5] Prepared by SC-186; Minimum Aviation System Performance Standards For Automated Dependent Surveillance Broadcast (ADS-B), RTCA/DO-242A, June 2002.

[6] Harry Hutchinson; Event Tree Probabilities, ACASA/WP1.6.3/213, November 2001, pages 25.

[7] Introduction to TCAS II Version 7, U.S. Department of Transportation, Federal Aviation Administration, November 2000, pages 45.

[8] Defining the Phrase: "Equivalent Level of Safety, Comparable to See-and-Avoid Requirements for Manned Aircraft", NASA Access 5, Work Package 2, CCA team, July 2004.

[9] Federal Aviation Administration, System Safety Study of Minimum TCAS II, DOT/FAA/PM-83/36, U.S. Department of Transportation, Washington, D.C., December 1983.

[10] Victor Carreno; Evaluation of a Pair-Wise Conflict Detection and Resolution Algorithm in a Multiple Aircraft Scenario, NASA TM-2002-211963, December 2002.

[11]Victor A. Carreño and César Muñoz; Implicit Intent Information for Conflict Detection and Alerting, Proceedings of the 23th Digital Avionics Systems Conference, DASC 2004, Salt Lake City, Utah, October 2004.

[12] Ronald Staab; Transmission/Reception Model for 1090 MHz ADS-B Mode S Extended Squitter, SAIC, Lanham, MD, May 2005.

[13] Vincent Mellon; TCAS II, Genie Out of the Bottle?, ASRS Directline, June 1993.

[14] Prepared by SC-186; Minimum Operational Performance Standards for 1090 MHz Automatic Dependent Surveillance – Broadcast (ADS-B), RTCA/DO-260, September 2000.

[15] Prepared by SC-186; Minimum Operational Performance Standards for 1090 Mhz Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic

[redacted]

Information Services – Broadcast (TIS-B), RTCA/DO-260, April 2003.

[16] FAA Order 8700.1 Change 3, Chapter 169, October 1989.

[17] Jeppesen, Aeronautical Information Manual, 2000.