Access 5 Project Office
NASA
P.O. Box 273
Edwards, CA 93523 USA
661-276-2440
661-276-3880 FAX
www.access5.aero

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Collision Avoidance Functional Requirements for Step 1

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Abstract: This Functional Requirements Document (FRD) describes the flow of requirements from the high level operational objectives down to the functional requirements specific to cooperative collision avoidance for high altitude, long endurance unmanned aircraft systems. These are further decomposed into performance and safety guidelines that are backed up by analysis or references to various documents or research findings. The FRD should be considered when establishing future policies, procedures, and standards pertaining to cooperative collision avoidance.

Status:

Access 5-Approved

Limitations on use:
This document represents thoughts and ideas of the Collision Avoidance work package team. It has not been reviewed or approved as an Access 5 project position on this subject. In addition to an integrated project review, some of the information also needs substantiation through simulation and further correlation with the technology demonstration data. Several of the performance guidelines contained within the appendix are substantiated using analysis, while others are based on values common to other collision avoidance systems currently in existence for manned aircraft. These values should be further analyzed to determine if they are sufficient for UAS. In addition there are still several TBDs found in Appendix A that need to be further explored and identified.

Revision 5 of this document was SEIT approved. In this revision 6, however, the updated performance guidelines have been reviewed only by the CA work package team. This deliverable was developed by analysis of cooperative collision avoidance. Additional work needs to address non-cooperative collision avoidance and surface collision avoidance.

NASA ACCESS 5

Collision Avoidance Functional Requirements for Step 1

Revision 6
February 13, 2006

Prepared by:

NASA ACCESS 5
Work Package 2, CA Team

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

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RECORD OF CHANGES

Revision	Date	Change Description
Version 1	7/9/04	
Version 2	9/30/04	Numerous updates made based upon CA WP review of Version 1 (July 2004). - Separated the CA requirements into Operational and Functional categories. - Added a Verification Matrix for each low-level functional requirement - Added Appendix A: Functional Requirement Trade-off Analysis - Added Appendix B: False Alert/Evasion Study - Added Appendix C: Conflict Avoidance Integrity, Fault Tolerance & Reliability
Version 3	4/28/05	Numerous changes based on comments received from FAA during the Mid-term Review (15-17 March 2005) - All requirements completely re-written - Functional requirements separated from performance/safety "guidelines" - Replaced the physical description of a notional UAS System and CA Subsystem with a purely functional architecture description - Top-level functional requirements from new FRD included in text - Added executive summary - Globally replaced "ROA" with "UAS", "FL400" with "FL430"
Version 4	7/19/05	Changes based on comments received from FAA and CA WP on 4 May 2005 - Edited text in numerous small ways, deleted irrelevant passages - Added a list of assumptions that govern the document, section 1.5 - Revised order of content in Introduction section - Added section 3.4 Functional Requirements Flow - Incorporated performance guidelines and supporting rationale/discussion material into Appendix A
Version 5	9/30/05	Changes based on comments received from FAA and CA WP on 29 July 2005 - Removed "Cooperative" from document title, and most of the body to reflect the generic nature of these functional requirements - Edited text of 3.4 (Functional Requirements Flow) to reflect the newest organization of functional requirements (7, rather than 8) - Added, deleted, moved around numerous performance guidelines - Removed the Display Guidelines from Appendix A
Version 6	2/13/06	Replaced a number of TBDs with values based on references and analysis

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EXECUTIVE SUMMARY

The Access 5 Project seeks to make unmanned flight in the National Airspace System (NAS) as routine as manned aircraft flight. To make this vision a reality there are several hurdles to overcome in the areas of technology, procedures, and policy. The Access 5 partners have organized to explore the requirements in each of these areas; one focus is in the area of collision avoidance. Significant reliance on technology will be required to provide a level of flight safety that is equivalent to manned flight. This document details the flow of collision avoidance requirements from the operational objectives down to the lower-level functional requirements for high altitude, long endurance (HALE) unmanned aircraft systems (UAS).

As a brief overview, the primary operational requirement of Access 5 is: "The HALE UAS shall operate routinely and safely in the NAS." Functional decomposition reduces this to the following four functions: Aviate, Navigate, Communicate, and Avoid Hazards. The Collision Avoidance (CA) task is completely contained within the "Avoid Hazards" function. This document exists to detail and justify the requirement flowdown process.

The functional requirements that define CA were initially derived from the six primary "sense and avoid" functions, as explored in the Equivalent Level of Safety (ELOS) document. They were then expanded to seven, as follows:

- Detect Traffic
- Track Traffic
- Evaluate Collision Potential
- Prioritize Collision Threats
- Determine Avoidance Maneuver
- Command Maneuver
- Execute Maneuver

The logical flow of these functions can be depicted graphically, and such a Functional Flow Block Diagram is presented in section 3.4. There, one can see the points in the chronology of a potential cooperative air traffic encounter where the avoidance logic is called upon, and various exits from the flow when the situation is deemed "clear of traffic". This representation of the CA process is helpful in visualizing a typical in-flight scenario.

The document concludes with three appendices that provide additional detail on the requirements supporting the overall CA function. Appendix A decomposes the high level functional requirements into more specific performance guidelines. Appendix B suggests a methodology for verifying these requirements. Appendix C explores some interesting trade-offs to consider when establishing requirement values.

1.0 INTRODUCTION

1.1 Document Organization

This document is organized into the following sections and appendices:

- Section 1 – Introduction. States the background, purpose, and scope of this requirements document and its role in the Access 5 program. Also listed are the key assumptions.

- Section 2 – Applicable Documents. Identifies government and regulatory publications cited and referenced when defining the functional requirements and performance guidelines.

- Section 3 – Requirements. Specifies the functional requirements of the Step 1 CA subsystem and traces the requirements back to the unmanned aircraft systems high-level functional requirements.

- Section 4 – Definitions and Acronyms. A glossary of terms utilized throughout the document.

- Appendix A – Performance, Safety and Quality Guidelines. Provides a significant number of lower level requirements, or "guidelines", which would support a UAS manufacturer during the design process. Many of them include rationale and discussion that is based upon previous research and trade studies. The intent is to expand upon the basic seven CA functions, but not to mandate any particular values for a final product.

- Appendix B – Detailed Verification Matrix. Contains a verification matrix indicating how a typical UAS program might demonstrate that all of its requirements have been met. This tool will also be useful to the Access 5 CA work package in determining what simulations to develop.

- Appendix C – Functional Requirements Trade-off Analysis. Computational investigation of sample aircraft capabilities and their trade-offs.

1.2 Purpose

Due to the ever increasing density of today's air traffic, traditional "see and avoid" measures used by pilots are often supplemented by "sense and avoid" technologies. The most recent developments are *cooperative* transponder-based systems that interoperate to provide collision avoidance guidance or to promote enhanced situational awareness for pilots. These cooperative technologies include Traffic Alert and Collision Avoidance System (TCAS), Traffic Information Service-Broadcast (TIS-B), and the Automatic Dependent Surveillance-Broadcast (ADS-B) system. In addition, the FAA provides an air traffic separation service to all aircraft operating in Class A airspace or on an instrument flight rules (IFR) flight plan. These technologies and services have been credited with reducing the total number of midair collisions. As unmanned flight becomes increasingly reliable and useful, it may be necessary to adapt these collision avoidance technologies initially to remotely piloted vehicles, and eventually to aircraft featuring higher levels of autonomy. The first step in this process is development of the functional requirements that will govern this gradual transformation to the next generation of flight.

The intent of this paper is to establish the collision avoidance (CA) functional requirements for high altitude, long endurance (HALE) unmanned aircraft system (UAS) flight. Additionally, this document identifies the recommended performance and safety guidelines that should be considered when establishing future policies, procedures, and standards pertaining to cooperative collision avoidance.

1.3 Background

Access 5 is a national program sponsored by NASA, with participation by aerospace industry members, the Federal Aviation Administration (FAA), and the Department of Defense (DoD). Headquarters for this effort is the NASA Access 5 Project Office, located at NASA Dryden Flight Research Center in Edwards, CA. The goal is to enable civil HALE UAS to routinely operate in the National Airspace System (NAS) as safely as manned aircraft. Further objectives of Access 5 include assisting in the development of UAS policies and procedures, demonstrating that all requirements are reasonable and achievable, and identifying infrastructure to promote a robust civil market for HALE UAS.

Access 5 plans call for integrating HALE UAS into the NAS through a four-step process:

1. Routine operations of HALE UA at or above Flight Level (FL) 430 (43,000 feet) with take-offs and landings in pre-coordinated/restricted airspace.
2. Routine operations above FL180 (18,000 feet) with take-offs and landings in pre-coordinated or special use airspace.
3. Routine operations above FL180 and access to UAS-designated airports with emergency landings in restricted areas.
4. Routine operations above FL180 and access to UAS-designated airports, including emergency landings (i.e., true "file-and-fly").

Access 5 commenced in May 2004 and is slated to run for five or more years.

1.4 Scope

The scope of this document is limited to Step 1 of Access 5 and therefore will only address a limited range of UAS performance parameters. However, the functional requirements for collision avoidance will continue to be applicable to later steps in the program. The following constraints were used in developing the requirements and guidelines in this paper:

- The requirements apply to HALE UAS. These systems are defined by having an air vehicle element capable of performing mission objectives at FL430 or higher, and with sufficient cruise capability to transit the NAS.
- This document applies only to Step 1, which is concerned with avoiding *cooperative* traffic only. Cooperative traffic consists of those aircraft possessing an onboard transponder or other system which provides positioning information in 3-D space to air traffic control (ATC) and other aircraft. Non-cooperative aircraft, on the other hand, are not equipped with

such systems and therefore may require additional collision avoidance capabilities to achieve an acceptable level of safety.

- These requirements only address the *mid-air* collision case. The surface collision case is part of future study efforts.
- Finally, the functional requirements established in this document are to be considered minimum requirements to achieve a CA capability. Further detailed performance guidelines will promote a level of safety equivalent to manned aircraft avoiding cooperative traffic.

1.5 Assumptions

The requirements for Step 1 established in this document are based on the following set of assumptions:

1. There will be a requirement for 100% usage of cooperative technology. This is in accordance with ATC regulations for Class A airspace.
2. There will be positive air traffic control.
3. The UAS will perform no autonomous collision avoidance maneuvers.
4. The human pilot is a part of the UAS – most likely in the control station element.
5. The UAS will fly with an IFR clearance.
6. Collision avoidance activities begin when ATC-mandated separation breaks down.

As depicted in the Figure 1 “onion diagram”, the avoidance of traffic does not begin with the CA technologies of the UAS. Rather, it is accomplished using an integrated, multi-layered approach. This begins with aviation procedures and regulations that minimize traffic conflicts – for example, aircraft on an IFR flight plan flying a magnetic course of 0^{o} through 179^{o} fly at odd multiples of one thousand feet, while the remaining aircraft fly at even altitudes. The second layer is comprised of air traffic management systems such as ATC, which then perform de-confliction tasks to further reduce potential collision scenarios. Together, these two outer layers seek to ‘avoid conflicts.’ When they fail to provide adequate separation, the collision avoidance capabilities of each aircraft are called upon to avoid a mid-air collision. This final safeguard is the “sense and avoid” capability of the aircraft. Unmanned flight can only be a routine part of the NAS when the CA system used by a UAS provides an equivalent level of safety to manned flight. This document addresses the functional requirements for collision avoidance in a cooperative environment.

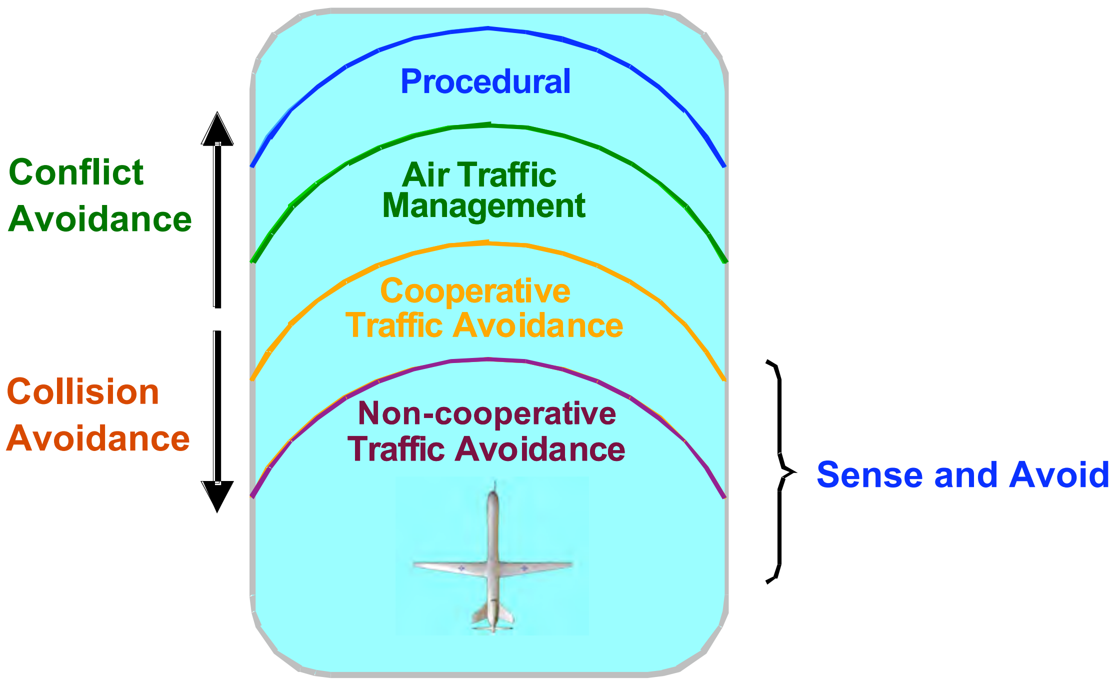

Figure 1: Layers involved in achieving air traffic separation

2.0 APPLICABLE DOCUMENTS

Listed below are documents used to develop the CA subsystem requirements. These may be referenced within this document to validate how a specific requirement was developed.

2.1 Government Documents

2.1.1 FAA Regulations

- 14CFR 21.21B, *"Airworthiness Requirements"*
- 14CFR 91.1, "*General Operating and Flight Rules–Applicability*"
    - 14CFR 91.111, "*Operating Near Other Aircraft* "
    - 14CFR 91.113, "*Right of Way Rules: Except Water Operations*"
    - 14CFR 91.123, "*General Operating and Flight Rules–Compliance with ATC Clearances and Instructions"*
    - 14CFR 91.155, "*Basic VFR Weather Minimums"*
    - 14CFR 91.179, *"IFR Cruising Altitude or Flight Level"*
    - 14CFR 91.215, *"ATC transponder and altitude reporting equipment and use"*

2.1.2 FAA Orders

- FAA Order 7110.65P, *"Air Traffic Control"*, 19 Feb 2004
- FAA Order 7610.4K, "*Special Military Operations"*, 19 Feb 2004
- FAA Order 8020.11, "*Aircraft Accident and Incident Notification, Investigation, and Reporting*"
- FAA Order 8110.4, paragraphs 2-10, *"ELOS Findings"*
- FAA Order 8700.1, Ch. 169. "*Investigate a Near Mid-Air Collision"*

2.1.3 Other FAA Documents

- *National Airspace System Systems Engineering Manual*, version 2.1, 13 Nov 2003
- *National Airspace System Systems Requirements Specification,* NAS-SR-1000, Change 10, 27 Nov 1991
- *FAA System Safety Handbook: Practices and Guidelines for Conducting System Safety Engineering and Management,* 30 Dec 2000
- FAA-P-8740-51, FAA Accident Prevention Program, "*How to Avoid a Mid Air Collision"*
- AC 90-48C Advisory Circular, "*Pilots' Role in Collision Avoidance*"
- AC 20-151 Advisory Circular, "*Airworthiness Approval of Traffic Alert and Collision Avoidance Systems (TCAS II) Version 7.0 and Associated Mode S Transponders*"
- TSO-C119b "*Traffic Alert and Collision Avoidance System (TCAS) Airborne Equipment"*
- TSO-C112 *"Air Traffic Control Radar Beacon System/Mode Select (ATCRBS/MODE S) Airborne Equipment"*

- TSO-C166 *"Extended Squitter Automatic Dependent Surveillance – Broadcast (ADS-B) and Traffic Information Service – Broadcast (TIS-B) Equipment Operating on the Radio Frequency of 1090 Megahertz (MHz)"*
- *Aeronautical Information Manual (AIM)*, Section 2, paragraph 4-2-1 "General"

2.1.4 Other Government Documents

- ICAO Annex 2, Rules of the Air, "*Right of Way Rules*". International Civil Aviation Organization, Ninth Edition, July 1990

2.2 Non-Government Documents

2.2.1 Industry Standards

- RTCA-DO-289, "*Minimum Aviation System Performance Standards (MASPS) for Aircraft Surveillance Applications"*
- RTCA-DO-185A, *"Minimum Operational Performance Standards (MOPS) for TCAS II Airborne Equipment"*

2.2.2 Industry Documents

- AOPA Air Safety Foundation, "*2003 Nall Report*", 2004 edition
- NASA Access 5 Project, "*HALE ROA Concept of Operations, Ver2*", March 2005
- NASA Access 5 Project, "*Functional Requirements Document, Rev2*", September 2005.
- NASA Access 5 Project, *"Defining the Phrase: 'Equivalent Level of Safety, Comparable to See-and-Avoid Requirements for Manned Aircraft',"* 27 Sep 2004

2.3 Order of Precedence

When conflicting requirements and guidance are present, government regulations will take precedence.

3.0 REQUIREMENTS

A complete listing of the operational and functional requirements for UAS operations is located in the Access 5 Step 1 Functional Requirements Document (FRD)[1].

3.1 Access 5 Operational Requirements

According to the Access 5 Concept of Operations (CONOPS)[2], the overall goal of the program is for HALE UAS to operate routinely and safely within the National Airspace System (NAS). The CA function will support this operational requirement via the high level functional requirement "Avoid Hazards" (section 3.2.4). Access 5 Operational Requirement O1.3 is "The UAS shall meet an equivalent level of safety to that of a manned general aviation aircraft." Operational Requirement O2.1 is "UAS operations shall comply with all applicable 14CFR Part 91 requirements." The CA function supports both of these by fulfilling, in particular, the requirement for sense and avoid in 14 CFR Part 91.113, "*Right of Way Rules: Except Water Operations.*"

3.2 UAS Functional Requirements

The Access 5 Systems Engineering and Integration Team (SEIT) performed a functional analysis on an unmanned aircraft system. One of the resulting products was a hierarchical structure of the major functions that comprise any UAS. In accordance with the NAS Systems Engineering Manual[3], these functions together should describe what the UAS must be capable of doing in order to produce the desired behavior described by the operational requirements. Figure 2 depicts these high level functions, which together support the HALE UAS operational requirements. The SEIT identified four high level functions which together enable the UAS to perform everything needed to operate routinely and safely in the NAS. These functions are: (1) Aviate, (2) Navigate, (3) Communicate, and (4) Avoid Hazards. While each of these functions are defined later in this section, further details regarding these functions as well as their lower level functional breakouts can be found in the Access 5 Step 1 Functional Requirements Document and in requirements documents specific to the various work packages.

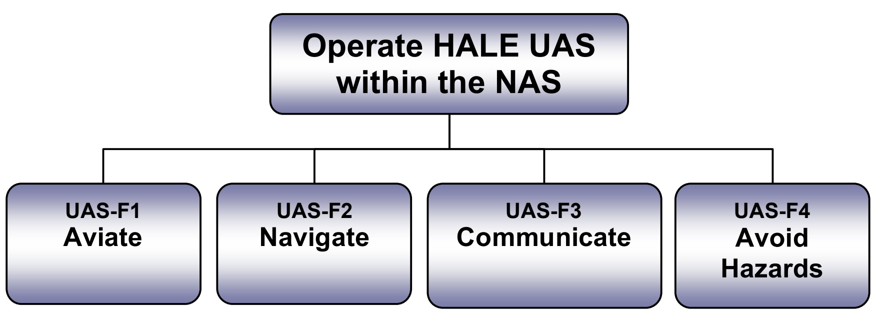

Figure 2: UAS High Level Functions

[1] NASA Access 5 Project, "*Functional Requirements Document, Rev 2*", September 2005.
[2] NASA Access 5 Project, "*HALE ROA Concept of Operations, Ver2*", March 2005.
[3] Federal Aviation Administration "*NAS Systems Engineering Manual, Ver3.0*", 30 September 2004, pg. 4.3-22.

3.2.1 UAS-F1: Aviate

The UAS shall be able to aviate within the NAS. Aviating includes both controlling and monitoring the aircraft and all of its systems necessary for taxi, takeoff, climb, maneuver, cruise, approach, descent, and landing or recovery.

3.2.2 UAS-F2: Navigate

The UAS shall be capable of maintaining navigational control while operating in the NAS. Three essential elements to navigation include maintaining knowledge of the current position, the destination, and how to get to the destination. Navigation can be accomplished both strategically and tactically. While a traditional flight plan requires more time to complete and would be considered strategic, in-flight maneuvering would be considered a form of tactical navigation.

3.2.3 UAS-F3: Communicate

The UAS shall be able to exchange information (data or voice) with all entities needed to maintain safe and reliable UAS operations. These entities could be both internal and external to the UAS. External interfaces would typically include ATC and other aircraft, while internal interfaces might include control stations and ground support.

3.2.4 UAS-F4: Avoid Hazards

The UA shall avoid hazards while operating in the NAS. These hazards include terrain, hazardous weather, and other traffic – both airborne and on the ground. "Terrain" includes natural features as well as man-made structures, while ground traffic includes other aircraft, vehicle, and human traffic. "Hazardous weather" typically would include thunderstorms and icing conditions. However, this may vary based on the structural characteristics of the UA being flown. The CA function directly supports UAS-F4.

3.3 CA Functional Requirements

Cooperative collision avoidance provides the capability to meet the Step 1 requirement to avoid traffic hazards in the NAS. Should the guidance provided by ATC fail to avoid a conflict, the remaining methods of achieving safety are the following:

- The other aircraft maneuvers to avoid collision. This can only happen if that aircraft has a means to detect the UA and still allow sufficient time to maneuver. Avoidance can also be aided if the UA (own ship) is easily detectable – having an active transponder, lights, or bright paint, for example.
- The UA maneuvers to avoid collision. This requires active sensors, communications with other aircraft, and/or CA technology.

In some cases, both of these methods will be employed simultaneously. Ideally, both aircraft would perform a coordinated maneuver that leads to successful avoidance. However, in order to achieve an equivalent level of safety to manned aircraft, one can not assume that ATC guidance is infallible, or that the other aircraft will maneuver. Thus, the CA functional requirements must ensure that a successful own ship avoidance maneuver can be reliably achieved, and is acceptable for the environment in which the UA is flying.

A functional break-out of the higher level “Avoid Hazards” function (UAS-F4) is shown in Figure 3. All of the CA Functional Requirements found within this document can be traced back directly to this high level UAS function through the lower level function to “Avoid Other Traffic” (UAS-F4.1) within the UAS functional hierarchy.

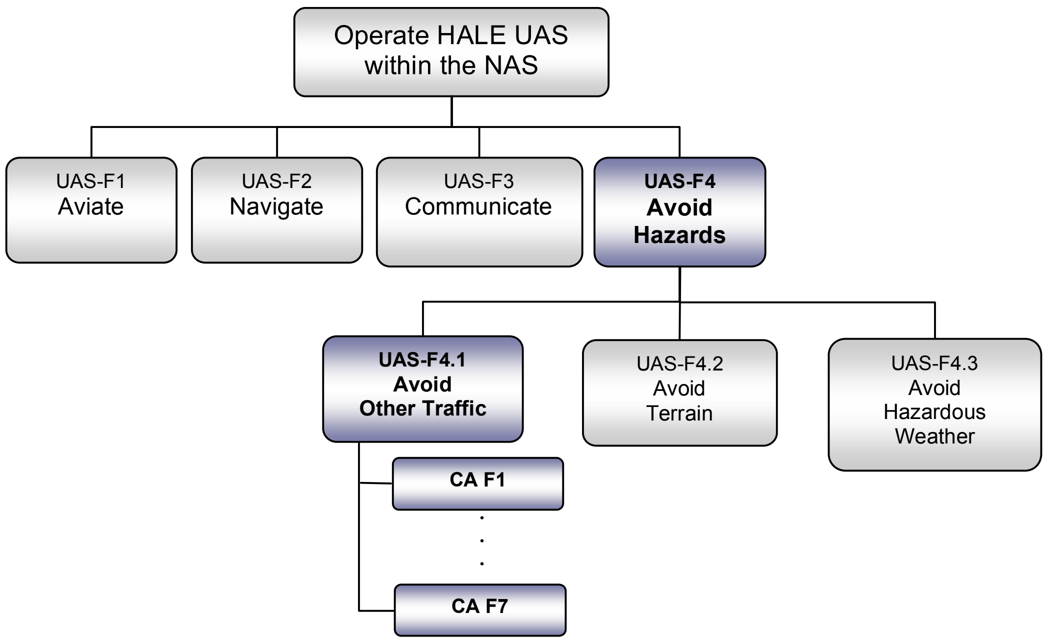

Figure 3: Lower-Level Break-out of the Avoid Hazards Function (UAS-F4)

The following sections comprise what should be considered the minimum threshold set of functional requirements needed by a UAS to avoid collisions with other aircraft.

3.3.1 CA F1: Detect Traffic

The Collision Avoidance System shall detect traffic within its surveillance volume.

Note 1: The “surveillance volume” is defined by three performance characteristics of the Collision Avoidance System: detection range, azimuth field of regard, and elevation field of regard.

Note 2: For Step 1, this refers only to cooperative traffic, which is defined as other aircraft that broadcast positional information using an altitude-encoding transponder.

Note 3: If this function includes conveying data to the UAS pilot, then there must be a human-system interface in place to accomplish this task.

3.3.2 CA F2: Track Traffic

The Collision Avoidance System shall track the detected traffic.

Note 1: A "track" is established when a state estimate is developed with sufficient confidence. This estimate includes the traffic element's position and velocity vector.

Note 2: If the UAS pilot is to perform any part of this function, then the relevant detected traffic data must be conveyed to the pilot.

3.3.3 CA F3: Evaluate Collision Potential

The Collision Avoidance System shall evaluate the potential for collision with each traffic element being tracked, including the assessment of existing collision threats.

Note: If the UAS pilot is to perform any part (or all) of this function, then the tracked traffic data must be conveyed to the pilot.

3.3.4 CA F4: Prioritize Collision Threats

The Collision Avoidance System shall prioritize the traffic posing a collision threat.

Note 1: Traffic elements that have been deemed collision threats will be ranked based on time to collision, or other similar criteria.

Note 2: If the UAS pilot is to perform any part (or all) of this function, then the collision evaluation data must be conveyed to the pilot.

3.3.5 CA F5: Determine Avoidance Maneuver

The Collision Avoidance System shall determine an avoidance maneuver that prevents a collision.

Note 1: The role of the human pilot in CA F5 may vary depending on policy or design decisions:
A) The pilot may determine the maneuver without assistance from any collision avoidance logic.
B) The pilot may take into consideration the information provided by collision avoidance logic to help make a determination.
C) The pilot may rely solely upon the maneuver determined by the collision avoidance logic.
D) The pilot may have no interaction with the maneuver decision whatsoever. In Access 5, Step 1, option D is removed from consideration since autonomous maneuvers have been assumed to be out of scope.

Note 2: If the UAS pilot is to perform any part (or all) of this function, then the prioritized collision threat data must be conveyed to the pilot.

3.3.6 CA F6: Command Maneuver

The Collision Avoidance System shall command an appropriate avoidance maneuver.

Note 1: The commanded maneuver can include initiating a new maneuver, continuing an ongoing maneuver, or terminating an avoidance maneuver if a collision threat no longer exists.

Note 2: In Step 1 it is assumed that the human pilot is part of the CA system and will initiate the maneuver, since autonomous maneuvers have been assumed to be outside the scope of Step 1.

3.3.7 CA F7: Execute Maneuver

The Collision Avoidance System shall perform the commanded maneuver.

Note 1: This CA functional requirement is essentially performed by the maneuver element of the top level "Aviate" function.

Note 2: The UAS may need to communicate the performance of a maneuver to ATC, per the stipulation in 14CFR 91.113.

3.4 Functional Requirements Flow

The seven collision avoidance functions that comprise the Avoid Other Traffic function (UAS-F4.1) are most easily visualized and understood in the context of a Functional Flow Block Diagram (FFBD). This system engineering tool indicates the sequential relationship of a system's functions, the flow of information between functions, decision points, and iterative loops. Figure 4 is an excerpt from a high level FFBD and depicts the continuous nature of the 'Avoid Collisions With Other Traffic' function during flight. It would normally be part of a larger diagram that includes all other functions at the same level (e.g Avoid Hazardous Weather, Avoid Collisions With Surface.)

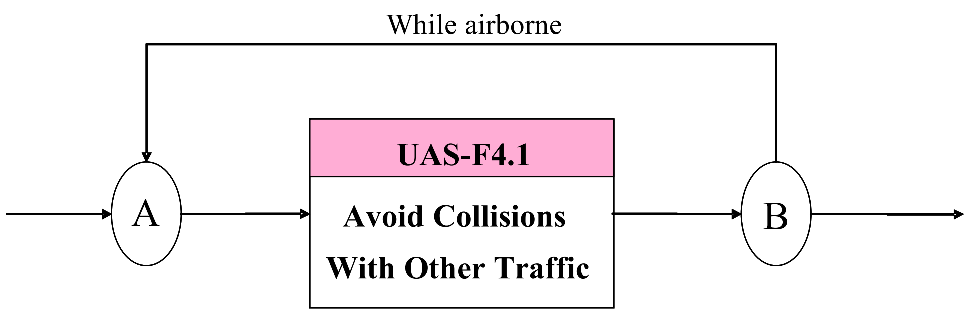

Figure 4: Avoid Other Traffic FFBD segment

To gain insight into this "black box", one decomposes the block to the next level, as shown in Figure 5. The points marked "A" and "B" in Figure 4 are now the beginning and end of the F1-F7 functional flow that performs UAS collision avoidance. The following paragraphs will detail this flow, and clarify the various logic gates that control it.

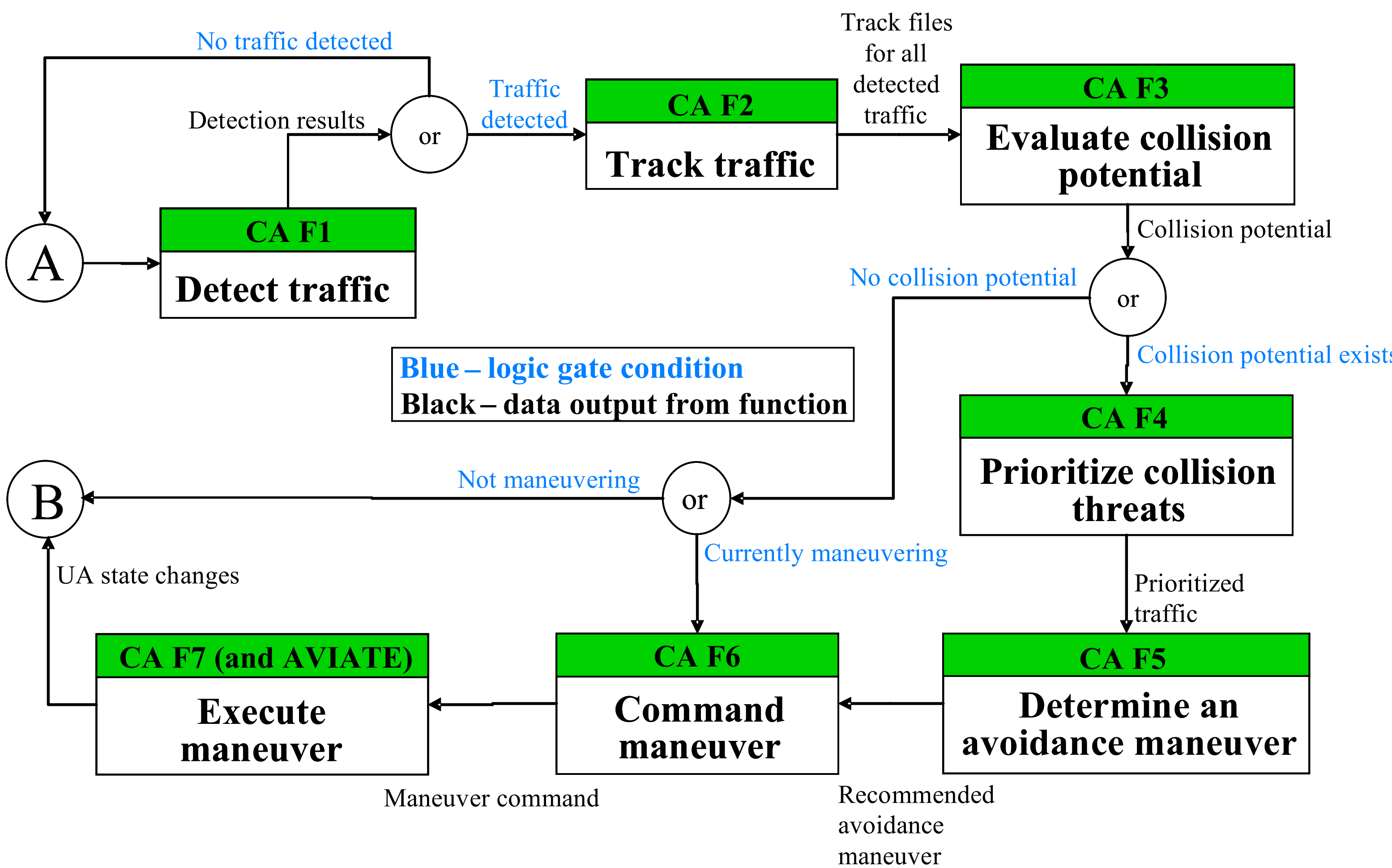

Figure 5: FFBD for Function "Avoid Collisions with Other Traffic"

CA F1: Detect Traffic
Detection of cooperative traffic elements is the function that drives the entire CA process. The rate at which the entire flow repeats is the update rate of the transponder or other sensing device used by the UAS. If no traffic is detected, then the flow for that instance is complete and no further functions are performed. This is shown in Figure 5 by the loop back to the beginning (point "A".) If there *are* detections, the flow continues onward to process the traffic information.

CA F2: Track Traffic
The *Track Traffic* function requires information obtained during earlier iterations to determine if the detection in this time step can be correlated to data previously collected. The function, therefore, represents more than using the detection data just received; it includes processing the new detection(s) with data previously obtained. This information is used to establish a track history for each detected traffic element.

CA F3: Evaluate Collision Potential
This function determines the likelihood of collision with each traffic element being tracked. Notionally, the function projects the track forward to determine its closest point of approach, and then compares that to pre-set avoidance thresholds. If one or more tracks exceed the threshold and pose a threat to the UA, then these evaluations are passed to the next function for prioritization. If no threat exists, then there is no need for the process flow to continue and it branches to the end of the loop (point "B" in Figure 5.) This function also serves to evaluate whether an ongoing own ship avoidance maneuver is successfully decreasing the collision risk. If the maneuver has succeeded in removing the risk, then the flow branches to F6 where "terminate maneuver" is then commanded.

CA F4: Prioritize Collision Threats
All traffic elements that are projected to pose a collision threat are prioritized in this function. The most likely sort parameter is "time to collision", or the number of seconds remaining before a threat is projected to breach the collision threshold of the UA, as defined in F3.

CA F5: Determine an Avoidance Maneuver
This function utilizes collision avoidance logic to recommend an avoidance maneuver that will prevent a collision from occurring. While the logic will focus on the primary threat identified in F4, it will also consider how each possible maneuver will affect collision potential with any other tracked elements. During the course of an ongoing maneuver, this function may refine (or possibly reverse) the current advisory, based on the output of the preceding functions.

CA F6: Command Maneuver
In Step 1, the UAS pilot is responsible for inputting the maneuver command. He/she will have received a maneuver advisory from the preceding function, and there may be data displays from which the pilot might gain some situational awareness to additionally inform the decision.

CA F7: Execute Maneuver
The command that is input in F6 is relayed to the UA. At this point, the top level "Aviate" function becomes responsible for initiating or maintaining the commanded maneuver. This

function completes the sequential flow depicted in the FFBD, which then starts once again with the next sensor update (point “A” in Figure 5.)

4.0 DEFINITIONS AND ACRONYMS

4.1 Definitions

Advisory – A message given to alert the crew of converging aircraft and/or a potential collision.
Air Traffic Control (ATC) – A service operated by an appropriate authority to promote the safe, orderly and expeditious flow of air traffic.
Alert – Indication (aural or visual) that provides information to the flight crew in a timely manner about a converging aircraft or a potential collision.
Closest Point of Approach – The minimum distance separating two air vehicles as they encounter one another.
Cooperative Traffic – Traffic that broadcasts position or other information, which assists in detecting and assessing conflict potential.
Equivalent Level of Safety (ELOS) – A determination that UAS operation has the same amount of risk (or better) to people and property as routine operation of a traditionally piloted aircraft.
False Alert – An alert that is generated when no collision potential exists based on the current UA flight path.
Flight Level (FL) – Flight altitudes above 18,000 MSL related to reference datum of 29.92 inches of mercury (e.g. FL250 represents a barometric altimeter indication of 25,000 feet).
High Altitude Long Endurance (HALE) UAS – A UAS capable of performing the mission objectives at an altitude of 43,000-foot mean sea level or higher. It will also possess sufficient cruise capability to transit the NAS – at least 24 hours in duration.
Manned Aircraft – Aircraft that are piloted by a human onboard.
Non-Cooperative Traffic – Traffic that does not broadcast position or other information.
Nuisance Alert – An alert that is given when an aircraft is in the collision avoidance operational envelope and a maneuver by the UA is not necessary to achieve satisfactory aircraft separation. (This terminology is consistent with early TCAS definitions.[2])
Resolution Advisory (RA) – Aural annunciation and display information provided by the collision avoidance subsystem to a flight crew, advising that a particular maneuver should, or should not, be performed to attain or maintain safe separation distance from an intruder aircraft.
Sense and Avoid – The ability to sense traffic which may create a conflict, evaluate flight paths, determine traffic right-of-way, and maneuver to avoid other traffic.
Threat – An intruder aircraft that has satisfied the threat detection logic and thus requires an avoidance maneuver
Traffic – Any air vehicles that might be encountered by the UA.
UAS – The Unmanned Aircraft System includes the UA, the control station (which includes the human pilot), and all associated communications hardware.

4.2 Acronym List

ADS-B	Automatic Dependent Surveillance-Broadcast
AOPA	Aircraft Owners and Pilots Association
ATC	Air Traffic Control
ARTCC	Air Route Traffic Control Center
BLOS	Beyond Line of Sight
C2	Command and Control
CA	Collision Avoidance
CAS	Collision Avoidance System
CCA	Cooperative Collision Avoidance
CFR	Code of Federal Regulations
CONOPS	Concept of Operations document
DoD	Department of Defense
DSA	Detect, See, and Avoid
ELOS	Equivalent Level of Safety (see Definitions)
FAA	Federal Aviation Administration
FFBD	Function Flow Block Diagram
FL	Flight Level
FOR	Field of Regard
FOV	Field of View
FRD	Functional Requirements Document
HALE	High Altitude, Long Endurance (see Definitions)
IFR	Instrument Flight Rules
LOS	Line of Sight
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NMAC	Near Mid-Air Collision
RA	Resolution Advisory (see Definitions)
SEIT	Access 5 Systems Engineering Integration Team
TCAS	Traffic Alert and Collision Avoidance System
TRL	Technology Readiness Level
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
VFR	Visual Flight Rules

APPENDIX A: PERFORMANCE AND SAFETY GUIDELINES FOR COOPERATIVE COLLISION AVOIDANCE

For Step 1 of Access 5, the Collision Avoidance (CA) function shall provide the UAS pilot with the ability to operate the vehicle above FL430 without colliding into other cooperative aircraft. To successfully accomplish this, the UAS must be able to perform each of the seven functions listed below. All of these are derived from the six "sense-and-avoid" functions that are outlined in the Equivalent Level of Safety (ELOS) document[4], which was also developed under the Access 5 Project.

F1 – Detect traffic

F2 – Track traffic

F3 – Evaluate collision potential

F4 – Prioritize collision threats

F5 – Determine avoidance maneuver

F6 – Command maneuver

F7 – Execute maneuver

Each of these is equally important to the overall objective of the CA function. In the first section, each of these functions are re-stated as the functional requirements introduced in section 3.3, and are then broken down into the "performance guidelines" which support that particular function. In this way, a parent-child relationship is established which will allow for eventual verification of all the CA functional requirements. Following this is a set of additional guidelines relating to overall CA system quality.

A.1 Performance Guidelines

These suggested system performance requirements, or "guidelines" provide clarification and quantification of the CA functional requirements that are the focus of this document. Many of the guidelines have a justification section, based on analysis and/or the results of previous CA research: the 2004 Sensor Trade Study[5] performed by the CA work package, and the ROA DSA requirements study[6] performed in 2003 for the ERAST program, a precursor to Access 5.

A.1.1 CA F1: Detect Traffic

The Collision Avoidance System (CAS) shall detect traffic within its surveillance volume.

A.1.1.1 Minimum Detect Time

The CAS shall detect traffic with sufficient time remaining for successful performance of all required collision avoidance functions.

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[4] NASA Access 5, *Defining the Phrase: "Equivalent Level of Safety, Comparable to See and Avoid Requirements for Manned Aircraft".* Revision 3, 27 Sep 2004, pg. 13.

[5] CA Sensor Trade Study Report, Work Package 2, 30 Oct 2004

[6] "Non-Cooperative Detect, See & Avoid Requirements for ROA Operations within Civil Airspace", NASA ERAST, 30 September 2003

Note: This Minimum Detect Time includes the delays resulting from sensor update rates, track establishment, command and control activities, ATC communications, on-board and off-board processing, pilot reaction time, and UA platform reaction time.

Discussion/rationale: Minimum Detect Time (MDT) is the most critical operational measure of a CAS, as it determines the amount of time that the UAS has to recognize a potential conflict and take action to avoid it. Estimated times associated with this topic are discussed in the ELOS document and conclude that for manned flight, the collision avoidance activities leading up to and including maneuver initiation require up to 12.5 seconds in order to consistently avoid mid-air collisions. However, this finding was derived using piloted aircraft, so it does not take any communication link delays into account. Further study and demonstration will provide more insight into the impact of these delays on MDT.

Two additional sources providing a nominal timeline for human based collision avoidance are: Advisory Circular 90-48C[7], and the "Mid-Air Collision Avoidance Document"[8] from Tyndall AFB. As shown in *Figure A.1*, 12.5 seconds is typically required for a pilot to detect an intruding aircraft, track the intruder aircraft's flight path, determine the collision potential with the other aircraft, decide upon an evasive maneuver, and then actually initiate the evasive maneuver. The original source of these estimates was never found; however, conversations with Air Force and FAA personnel pointed to a book called Human Factors in Aviation[9], which alluded to a military source, but did not actually identify the specific test or report. This source stated: "*Estimates of the time required to recognize an approaching aircraft and take evasive action range from 5.0 to 12.5 seconds…*" This estimate was for two jet aircraft with a closing velocity of 1100 miles per hour.

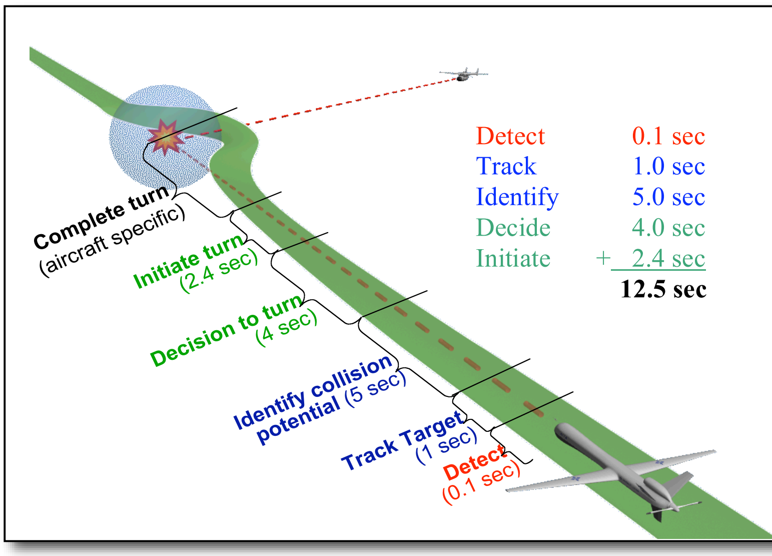


Figure A.1: Sample human pilot collision avoidance timeline

A third source for MDT values is the FAA document entitled "How to Avoid a Mid-air Collision."[10] This document states "*It takes a minimum of 10 seconds for a pilot to spot traffic, identify it, realize it is a collision threat, react, and have his aircraft respond.*" Based upon these three sources, the 12.5 second conclusion was the most conservative value for human pilot

[7] Advisory Circular AC 90-48C "*Pilots' Role in Collision Avoidance*", FAA, U.S. Dept. of Transportation
[8] "*Mid-Air Collision Avoidance Document*", Tyndall Air Force Base, 18 June 2001, www.tyndall.af.mil/maca/maca.htm
[9] Wiener, Earl & Nagel, David, "*Human Factors in Aviation*", Academic Press
[10] FAA-P-8740-51, FAA Accident Prevention Program, "*How to Avoid a Mid Air Collision*"

reaction times and is recommended for use as a baseline value when demonstrating an equivalent level of safety.[11]

It is important to note that this 12.5 second duration does not include the time necessary for the aircraft to actually complete the maneuver initiated by the pilot. This is dependent upon the performance capability of the aircraft, the type of maneuver performed -- climb or dive, heading change, or combination thereof -- and the aggressiveness of the maneuver. Another performance guideline (in F7) covers this aspect of the maneuver. Furthermore, the timeline presented here is further broken down into individual time requirements in sections F2-F6.

A.1.1.2 Detection Range

The CAS shall detect cooperative traffic at a range of at least TBD nautical miles.

Discussion/rationale: The detection range is the minimum distance at which the UAS must be capable of sensing cooperative traffic elements. This guideline is directly related to A.1.1.1 Minimum Detect Time. Essentially, it is the MDT multiplied by the closing velocity of the two aircraft. Figure A.2 shows the UA side of a lateral (banking) maneuver event. This analysis shows that with a bank angle above 12^o and airspeed of under 300 knots, a conservative separation distance of 500 feet can be achieved in under 5nm.

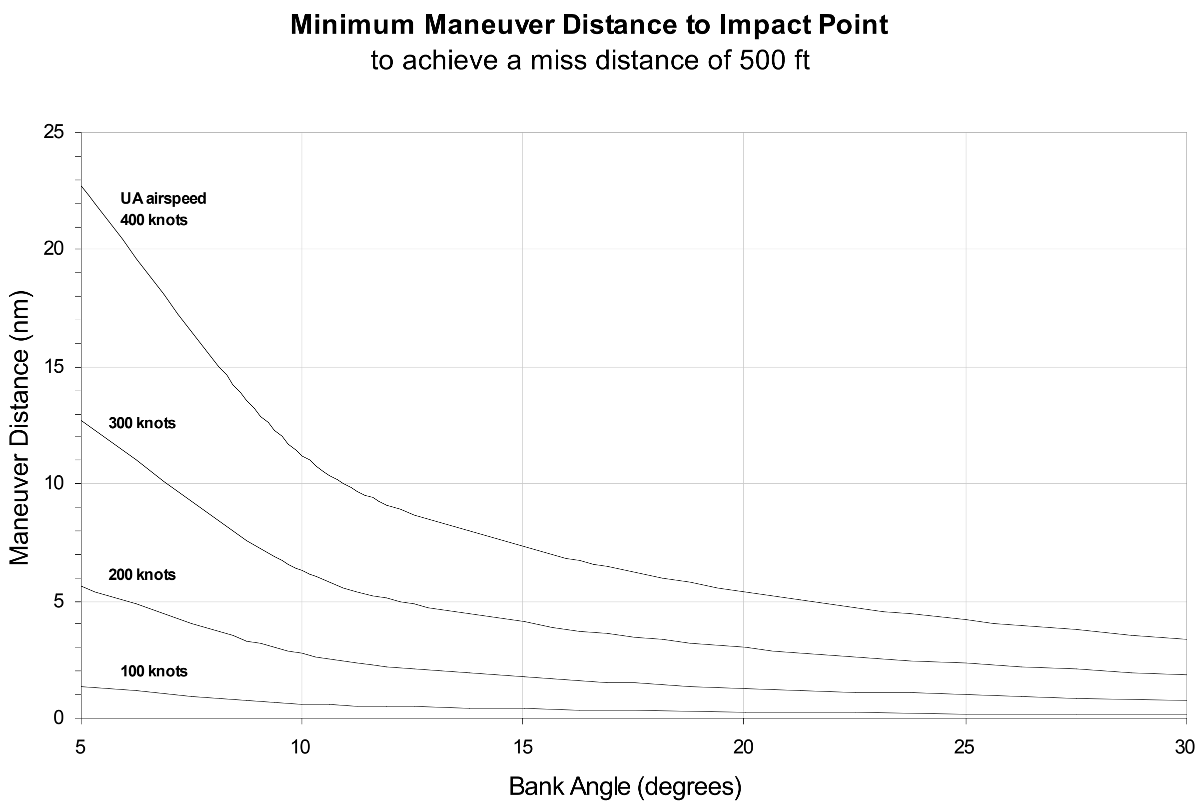


Figure A.2: Required lateral maneuver distance for various bank angles and airspeeds

[11] Wolfe, R. "*DSA Requirements for Remotely Operated Aircraft*". TTCP Meeting, Edwards, CA. October 2002

The “surveillance volume” of the UAS is defined by the detection range, azimuth field of regard, and elevation field of regard. The latter two are described in the following sections.

A.1.1.3 Azimuth Field-of-Regard (FOR)

The CAS shall detect cooperative traffic within an azimuth FOR of at least +/-110° referenced from the flight path of the UA.

Discussion/rationale: The FAA does not require a specific azimuth of visibility from the cockpit, but in general a pilot needs to see beyond 90° right and left, especially to check the airspace prior to a turn. Also, the FAR right-of-way rules require the converging aircraft to deviate to the right to avoid head-on conflicts, or deviate to the right to pass behind a conflicting aircraft approaching from the right. It is also the responsibility of an overtaking aircraft to avoid a slower air vehicle. The “ICAO Right of Way Rules (Annex 2)”[12] state that an aircraft intercepting from an aspect angle within +/-70° measured from the tail, must give way to the other aircraft. As shown in *Figure A.3*, the supplementary angle is therefore +/-110° from the nose of the aircraft. The FAA and Air Safety Foundation pilot information pamphlet “How to Avoid a Midair Collision”[13] states that looking +/-60° off the nose would catch the vast majority of conflicting aircraft. Thus, a Field of Regard (FOR) azimuth of +/-110° should be sufficient to provide detection equivalent to a manned aircraft, although more analysis may be required to fully validate this requirement.

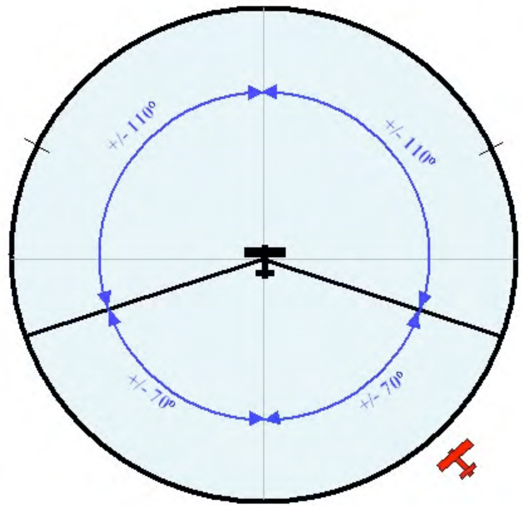


Figure A.3: Azimuth FOR based on ICAO Right of Way Rules

A.1.1.4 Elevation Field-of-Regard

The CAS shall detect cooperative traffic within an elevation FOR of at least +/-15° referenced from the flight path of the UA.

Discussion/rationale: Although the FAR does not require a specific elevation of visibility from the cockpit, it does require that climbing/diving aircraft give way to air vehicles above/below. The practical requirement, however, is vertical visibility relative to the aircraft’s climb/dive maneuver capability. “How to Avoid a Midair Collision” states that looking +/-10° in elevation (see *Figure A.4*) would catch “*virtually all conflicting aircraft*”.

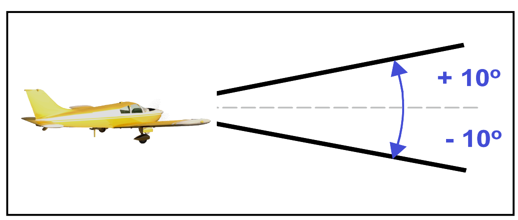


Figure A.4: Elevation FOR

[12] ICAO Annex 2, Rules of the Air, “*Right of Way Rules*”. International Civil Aviation Organization, Ninth Edition, July 1990

[13] FAA-P-8740-51, FAA Accident Prevention Program, “*How to Avoid a Mid Air Collision”*

Figure A.5 displays typical climb angles and rates for a variety of general aviation (GA), commercial, and military aircraft. From this graph it can be seen that most general aviation aircraft (1,000 to 1,500 fpm rate of climb) will in fact be detected if a pilot scans 15° above and below the horizon.

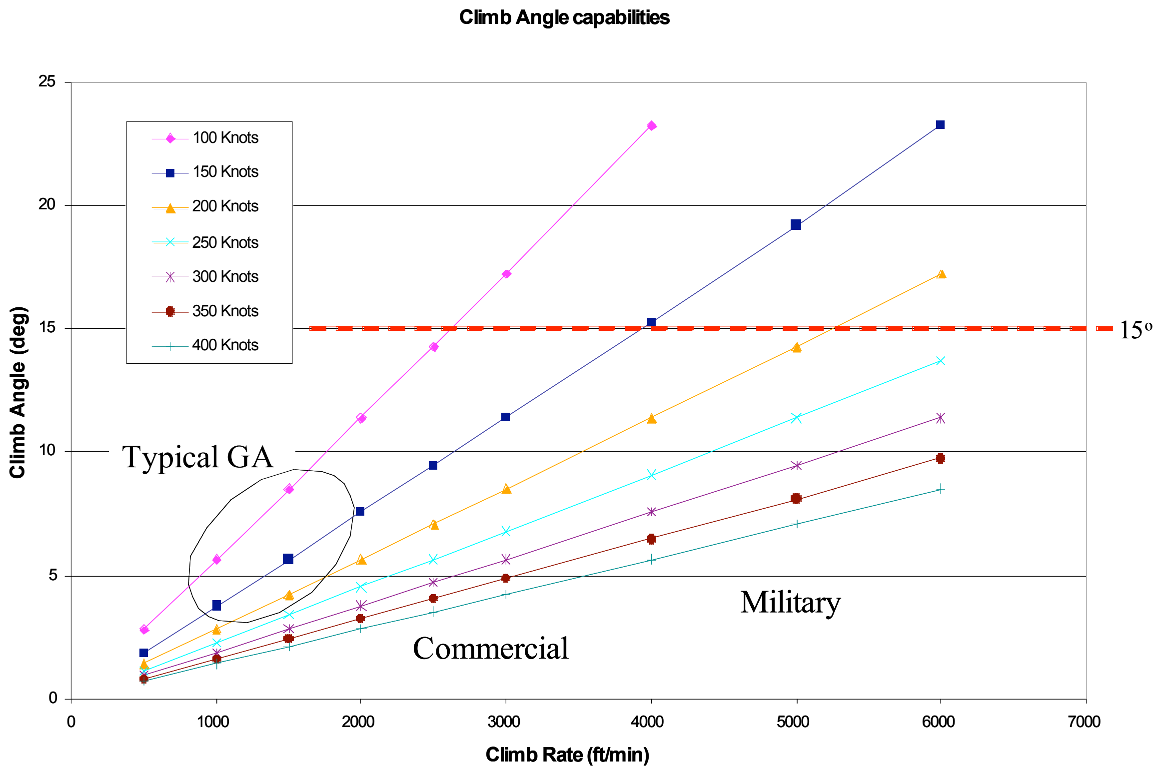
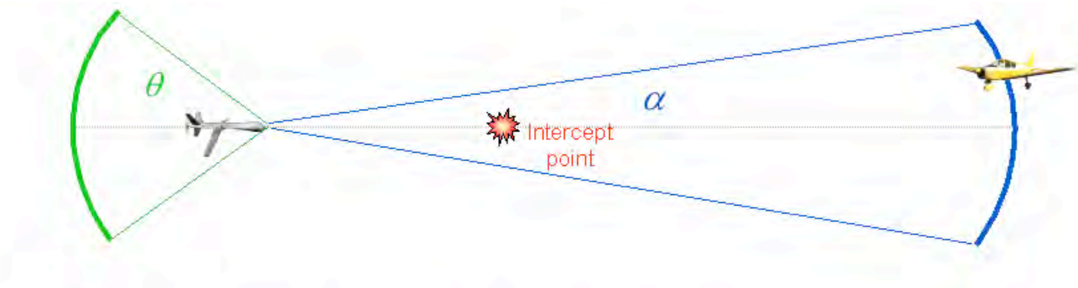


Figure A.5: Climb angles vs. Climb rates for various types of aircraft

As stated in "How to Avoid a Midair Collision", a sensor with an elevation FOR of +/-10° will detect most aircraft on collision trajectories flying in the opposite direction and approaching from within the front two quadrants (+/-90°). Upon further analysis, however, this generalization is not valid for aircraft traveling in the same general direction. Both head-on and overtaking scenarios are depicted in *Figure A.6*, in which the opposing traffic is approaching within the blue FOR angle, α, and the same direction traffic is approaching within the green FOR angle, θ. The table corresponding to this figure provides the results of an example scenario in which the UA is operating at 200 knots and the other aircraft is approaching at a range of speeds (100 to 600 knots). In this example, two sets of elevation angles were derived; one set for an aircraft rate of climb (roc) of 1,500 fpm, and the other set for an extreme climb rate of 6,000 fpm, which represents military aircraft. The results from this analysis are as follows:

- Frontal Collision Scenario – The worst-case elevation angle for the head-on collision scenario is always from a slower moving aircraft. For this example, 2.8° elevation FOR would be required to detect a 100-knot aircraft climbing/descending at 1,500 fpm, whereas 11.9° would be needed for a 100-knot aircraft climbing/descending at 6,000 fpm – a rather unlikely scenario.

- Overtaking Collision Scenario – The worst-case elevation angle for any overtaking collision scenario is from a conflicting aircraft flying at the same speed, as it will always be directly above or below the UA. The worst case elevation angle for an overtaking scenario is thus 90^o.
- θ_{max} is always greater than α_{max} – The maximum overtaking angle (θ_{max}) is always greater than the maximum frontal collision angle (α_{max}) for the same collision scenario.



Example: ROA Speed of 200 knot

Intruder Speed (knots)	Overtaking at 1,500 fpm roc θ	Frontal at 1,500 fpm roc α	Overtaking at 6,000 fpm roc θ	Frontal at 6,000 fpm roc α
100		2.8 deg		11.9 deg
200	90 deg	2.1 deg	90 deg	8.6 deg
300	8.5 deg	1.7 deg	32.2 deg	6.8 deg
400	4.2 deg	1.4 deg	16.8 deg	5.7 deg
500	2.8 deg	1.2 deg	11.3 deg	4.9 deg
600	2.1 deg	1.1 deg	8.5 deg	4.3 deg

Figure A.6: Example of a frontal and overtaking collision scenario with respect to elevation angles

From this analysis and the climb rate discussion related to Figure A.5, it is concluded that an elevation FOR of +/-15^o is sufficient to detect collision threats.

A.1.1.5 Detection Probability

The CAS shall detect cooperative traffic in the surveillance volume at a rate that supports the track probability guideline (A.1.2.3.)

Discussion/rationale: The CA system must reliably detect potentially conflicting traffic elements. The probability of detection reflects the system's ability to locate traffic within the defined surveillance volume with each scan or update made by the system. Work by the Air Force Research Laboratory and DRA in Ohio indicate that a 90% detection rate is comparable to a traditional piloted aircraft.[14] However, based upon the assumption that a track is established after three consecutive positive detections, a probability of 98.3%[15] is needed to support the 95% track probability suggested in A.1.2.3.

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[14] "See and Avoid for UAVs", DRA presentation to OSD, Crystal City, VA, 17 July 2001
[15] Note $(.983)^3 = .95$

A.1.1.6 Detection Rate

The average CAS detection rate shall be equal to or greater than 1.0 hertz.

Discussion/rationale: The detection rate is the frequency at which sensor data is gathered. As discussed in section 3.4.1, the other avoidance functions essentially operate at this same frequency. A low update rate may lead to a misdiagnosis of a conflict situation, especially if the conflicting traffic is maneuvering. Using the TCAS performance as a basis for evaluation, 1.0 Hz (an update every second) is determined to be the minimum acceptable rate. The actual surveillance period is a pseudo-random interval varied uniformly between 0.8 and 1.2 seconds. The jitter is required so false tracks will not be established by replies to other TCAS-equipped intruder aircraft or ground stations.

A.1.1.7 Detection Accuracy

The CAS shall detect cooperative traffic with accuracy in range, altitude, and azimuth determinations that is at least equivalent to the TCAS-II system.

Discussion/rationale:
As TCAS-II is a collision avoidance technology approved by the FAA, this discussion lists the sources of error that contribute to its overall performance. It can be assumed that an acceptable final guideline for detection accuracy will be at least as strict as the error bounds presented here.

Altitude error/accuracy. The table to the right is from DO-185A[16], section 3.2.8.1. It describes the pressure altitude accuracy assumed for both the TCAS-equipped airplane and the intruder aircraft (Mode C or Mode S). The error is assumed to be met with a 99.7% (3σ) confidence level.

Altitude	Error Bound (ft)
MSL	135
5k	144
10k	156
15k	174
20k	195
25k	213
30k	234
35k	258
40k	285

Range accuracy. DO-185A section 2.2.2.2.3 describes accuracy/error in range estimations. The overall range accuracy achievable by TCAS depends on the following error contributions to the measurement of reply arrival time:

a) Transponder reply delay and jitter
b) Apparent reply jitter due to the signal delay difference between the diversity transponder top and bottom antenna channel (including the cable and antenna location)
c) Apparent reply jitter due to transmit and receive delay differences between the TCAS top and bottom antenna channel (including the cable and antenna location)
d) TCAS range clock quantization
e) TCAS system noise

The first two error sources are associated with the transponder and are not under control of the TCAS manufacturer. Nevertheless, for received power levels at least 6 dB above the minimum trigger level (MTL) and for transponders meeting the characteristics specified in Mode S MOPS (DO-181A) TCAS should be able to achieve an overall range measurement with an error not

[16] RTCA-DO-185A, *"Minimum Operational Performance Standards (MOPS) for TCAS II Airborne Equipment"*

exceeding 50 ft RMS jitter for both Mode C and Mode S reports, a 250 ft bias for mode C reports, and a 125 ft bias for Mode S reports.

Independent of transponder effects, the TCAS-only range measurement error (considering only error sources c, d, and e above) will not exceed 35 ft RMS jitter for either Mode C or Mode S reports for received power levels at least 6 dB above MTL. As a result, the error for Mode S operation would be contained within a +/-175 ft band, and +/- 300 ft for Mode C.

Azimuth (bearing) accuracy. Primary bearing error contributors are the antenna manufacturing tolerances, antenna installation rotation and tilt, pattern disturbances due to reflections, antenna cable attenuation differences, receiver channel to channel amplitude differences, and TCAS system noise.

From DO-185A, section 2.2.4.6.4.2.1, with the standard ground plane (not installed on aircraft), the bearing error of the TCAS system shall not exceed 9^{o} RMS or 27^{o} peak for elevation angles between -10^{o} and $+10^{o}$. From DO-185A, section 2.2.4.6.4.2.2, the bearing error shall not exceed 15^{o} RMS or 45^{o} peak for elevation angles between $+10^{o}$ and $+20^{o}$. These errors account for the uninstalled system errors. The errors associated with installation are to be included separately.

A.1.1.8 False Detection/Nuisance

False detections shall occur at a rate that supports the false track guideline (A.1.2.6).

Discussion/rationale: Along with reliably detecting real objects, the system must not experience excessive false detections. The probability of false detection is the rate at which the CA system will mistakenly indicate the presence of a "ghost" traffic element. A Lockheed study[17] identified some potential causes, including navigation error, communication latency, data dropouts, and the validity of relative aircraft geometric information. Additionally, incorrectly received signals, such as those due to multi-path errors, should also be removed from the detection function. Improving the false detection rate by decreasing the Look Ahead Time can be traded off against the resulting reduction in decision time for the UAS. Clearly, an autonomous system would require less advance notice than a piloted one, but this is not the case in Step 1. Users should be informed of the inevitable occurrence of false detections when enlisting automated CA systems. A recommended false detection rate is on the order of 1%.

A.1.2 CA F2: Track Traffic

The Collision Avoidance System shall track the detected traffic.

Note: A "track" is established when a state estimate is developed with sufficient confidence. This estimate includes the traffic element's position and velocity vector.

[17] Lockheed Martin , *"CCA False Alert/Evasion Study"*, Appendix B to CCA FRD Rev 2, 2004.

A.1.2.1 Tracking Surveillance Volume

The CAS shall track cooperative traffic within an azimuth FOR of at least +/-110° and elevation FOR of at least +/-15° referenced from the flight path of the UA.

Note: The third dimension of the surveillance volume shall be defined according to the criteria in A.1.1.1 Minimum Detect Time and/or A1.1.2 Detection Range.

Discussion/rationale: See A.1.1.1 - A1.1.4 for rationale supporting the recommended surveillance volume.

A.1.2.2 Simultaneous Track Capability

The CAS shall be capable of simultaneously maintaining tracks on at least 35 cooperative aircraft in the UA platform's surveillance volume.

Discussion/rationale: The CA system is required to detect and simultaneously track multiple potentially conflicting traffic elements. The TSO-certified Skywatch traffic advisory system tracks up to 35 traffic elements. Although the system can track that many, only the 8 greatest threats are displayed to the user of the system.[18] Some sensors may filter data to avoid information overload and thereby allow a more succinct situational awareness for the pilot. Other sensors have bandwidth limitations. With aircraft densities being relatively low above FL430, the capability to track 35 intruders would be more than sufficient for Step 1 of Access 5.

A.1.2.3 Track Probability

The CAS shall establish a unique track on at least 95% of the cooperative traffic within the UA platform's surveillance volume.

Discussion/rationale: The FAA-certified TCAS II system specifies a 95% track probability, so it seems reasonable that the same threshold should be met or exceeded by any future CA system used in the NAS.

A.1.2.4 Track Quality

The CAS shall establish and maintain a track for traffic deemed eligible for collision avoidance with a confidence of TBD.

Note: "Eligible traffic" are those elements that exceed the threshold level of confidence as defined in this guideline.

Discussion/rationale: Confidence encompasses both the integrity of the data and the probability of detecting a target. Each CAS will be certified by end-to-end and component level testing before being used in the NAS.

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[18] Federal Air Regulations (FAR), Part 23, Subsection D, "*Design and Construction*"

A.1.2.5 Track Accuracy

The CAS shall maintain track accuracy that is sufficient to support the requirement to detect collision threats, and to not generate nuisance alerts on non-threats.

Discussion/rationale: Unless a reliable velocity can be obtained by the sensor, it is necessary to perform some filtering to smooth noise from measurements. This will help to satisfy both parts of the requirement. Too great a reliance on noisy measurements would cause delayed or missed necessary alerts, and would also lead to nuisance alerts. For maneuvering targets, the filtering must reflect a tradeoff between the smoothing of noise and the timely detection of trajectory changes. Furthermore, the design of a tracker must reflect the characteristics of the sensor used, as well as those of the target population (e.g. maneuvering).

A.1.2.6 False Tracks

False tracks shall account for no more than 1.2% of all tracks established by the CAS.

Note: A false track occurs when several false detections occur consecutively and trick the CAS into forming a "phantom" track.

Discussion/rationale: Guideline A.1.1.8 provides a list of factors that may contribute to false tracks being established. DO-185A[15] section 3.4.4.1 outlines a testing methodology for certifying a TCAS-II system receiving Mode C transponder transmissions. In it, 1.2% is provided as the maximum allowable false track rate, which is defined there as the ratio of the total number of false track-seconds to the total number of track-seconds associated with real aircraft. When receiving Mode S transponder input, the requirement becomes 0%. Since Mode S is not mandated for UAS, a probability of 1.2% is a reasonable threshold for this guideline.

A.1.2.7 Time to Establish Track

The CAS shall establish a track on detected cooperative traffic in the surveillance volume within TBD seconds of initial detection.

Discussion/rationale: The Tyndall study referenced in A.1.1.1 found that 1.0 second was typical for a pilot to track a potential threat. Since the UAS requires multiple detections to establish a track, and detections can be up to a second apart, it is unlikely that this same timeline can be met. However, a trade-off is possible since the time required to evaluate collision potential, prioritize threats, and determine an appropriate maneuver (F3-F5) will be much quicker using collision avoidance logic.

A.1.3 CA F3: Evaluate Collision Potential

The Collision Avoidance System shall evaluate the potential for collision with each traffic element being tracked, including the assessment of existing collision threats.

A.1.3.1 *Threat Evaluation*

The CAS shall continuously determine if any detected traffic elements pose a collision threat to the UA.

Discussion/rationale: A "collision threat" can be defined as any traffic element that is projected to breach the virtual "hockey puck" surrounding the UA. The dimensions of this relatively short, wide cylinder of airspace, centered on the own ship, are arbitrary and subject to further discussion. This particular shape, however, is a reasonable selection for two reasons: a) The horizontally-oriented wingspan of every air vehicle is much greater than its height. b) Typical flight procedures in Class A airspace rely heavily on level flight, which means that safety can be maintained with smaller separations in the vertical direction.

A.1.3.2 *Time to Classify Collision Potential*

The CAS shall determine the potential for collision posed by each tracked traffic element within TBD seconds of track establishment.

Discussion/rationale: The Tyndall AFB Midair Collision Avoidance document lists the human standard as approximately five seconds to identify the collision potential.[19] Based on this analysis, the CAS should be able to process the traffic tracking data and determine if an imminent conflict must be avoided within the same time limitation, and quite possibly much more quickly.

A.1.3.3 *Maneuver Completion*

The CAS shall determine and indicate to the pilot when the collision potential has been removed so routine mission activities can be resumed.[20]

Discussion/rationale: The Functional Flow Block Diagram in section 3.4 indicates why this guideline is a necessary part of F4. Basically, if the maneuver has removed all threat of collision with the tracked traffic elements, the flow branches to F6 where a "terminate maneuver" command is issued so that normal operations may resume.

A.1.4 CA F4: Prioritize Collision Threats

The Collision Avoidance System shall prioritize the traffic posing a collision threat.

A.1.4.1 *Multiple Threat Prioritization*

The CAS shall prioritize every traffic element that has been deemed a collision threat.

Note: "Time-to-collision", or the calculated time until the threat breaches the UA's hockey puck-shaped airspace (see A.1.3.1), is the criterion by which prioritization will occur.

[19] "*Mid-Air Collision Avoidance Document*", Tyndall Air Force Base, 18 June 2001
[20] In accordance with SAE ARP4153 paragraph 8.3.3.3

A.1.4.2 *Time to Prioritize Threats*

The CAS shall prioritize the collision threats within TBD seconds of collision potential classification.

A.1.5 CA F5: Determine Avoidance Maneuver

The Collision Avoidance System shall determine an avoidance maneuver that prevents a collision.

A.1.5.1 *Recommended Maneuver*

The CAS shall determine a feasible avoidance maneuver that prevents a collision with the most immediate threat from occurring.

Discussion/rationale: The avoidance maneuver can include a turn, climb, descent, or climb/descent in combination with a turn, constrained by the aeronautical capabilities of the UA. An important consideration is for the recommended maneuver to be compatible and coordinated with a threat that is simultaneously maneuvering (see A.2.4.3.) Additionally, the recommended avoidance maneuver should comply with the current "right of way" rules[21] and be compatible with CA systems currently utilized in the NAS. For example:

1. If the UA has a TCAS-II and is operated in RA mode, then the UA will be expected to perform the same maneuver as a manned aircraft.
2. If the UA has a TCAS-II in TA only mode, it must not disturb the established TCAS protocol.

A corollary requirement that is also valid: The CAS shall not fail to recommend a collision avoidance maneuver in a situation that requires one. This is known as an "unresolved collision" or "unresolved evasion."

A.1.5.2 *Multiple Collision Threats/Induced Collision*

The rate that the CA subsystem provides maneuver guidance that creates a more hazardous situation shall be on the order of $1.0X10^{-6}$ per flight hour.

Discussion/rationale: The selection of avoidance maneuver must also take into account any other tracked and prioritized traffic elements. An induced collision occurs when a CAS advisory is followed and leads to a collision (or near mid-air collision) when taking no action whatsoever would not have led to a collision event. This requirement leads to an additional, but critical level of complexity in the collision avoidance logic. It is also related to the Unnecessary Evasion requirement (A.1.5.3), in that it is an incorrectly advised maneuver. AC 23.1309-1C[22] provides guidance regarding catastrophic events such as an induced collision. Figure 2 in section 9.b.3 indicates that a Class IV aircraft (commuter category) has an allowable probability of catastrophic failure of less than 10^{-9}. This is relaxed to 10^{-6} for Class I vehicles (small general aviation aircraft.)

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[21] CFR 91.113, "Right of Way Rules: Except Water Operations"

[22] Advisory Circular 23.1309-1C "Equipment, Systems, and Installations in Part 23 Airplanes", March 1999.

A.1.5.3 *Unnecessary Evasion*

The probability of an unnecessary evasion maneuver advisory being generated without failure annunciation shall be on the order of $1X10^{-4}$ per flight hour in the terminal environment and $1.0X10^{-5}$ per flight hour in the en route environment.

Discussion/rationale: A University of Illinois paper on automated CA devices[23] posits the following: "It is not possible to determine a fixed threshold for an 'acceptable' false alert rate due to the complexity of constructs such as trust and workload … as well as the diversity of the operational environments and settings in which alerting systems are used. The false alert tolerance could be increased by improving the ROA pilot's general awareness of the traffic situation." In other words, in order to avoid the "cry wolf" phenomenon in which pilots ignore or mistrust frequent collision alerts, steps must be taken to ensure that the pilot has the best possible data upon which to base maneuver decisions. The values given are based on current commercial collision avoidance systems.

A.1.5.4 *Adjust for Maneuver*

The CAS shall revise the maneuver recommendation when other aircraft are simultaneously maneuvering.[24]

Note: A maneuver revision may not be necessary, but the CAS should be capable of a mid-maneuver adjustment, similar to a TCAS reversal advisory.

A.1.5.5 *Time to Determine Maneuver*

The CAS shall notify the UAS pilot of the recommended avoidance maneuver with sufficient time remaining to initiate the maneuver and avoid collision.

Discussion/rationale: The Tyndall AFB report estimates the human capability as approximately 4 seconds to decide on an evasive maneuver. This is the value that the ELOS document uses in its calculation of the expected duration of sense-and-avoid functions.

A.1.6 CA F6: Command Maneuver

The Collision Avoidance System shall command an appropriate avoidance maneuver.

A.1.6.1 *Pilot Response Time*

The UAS shall command an avoidance maneuver within TBD seconds of a collision avoidance maneuver being advised by the CAS.

Note: The pilot is considered an integral part of the UAS, and in Step 1 will be ultimately responsible for commanding an avoidance maneuver.

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[23] Thomas, Wickens, Rantanen, Institute of Aviation, Aviation Human Factors Division, UIUC, *"Imperfect Automation in Aviation Traffic Alerts: A Review of Conflict Detection Algorithms and their Implications for Human Factors Research"*, 2003.

[24] In accordance with SAE ARP4153 "Human Interface Criteria for Collision Avoidance Systems"

Discussion/rationale: The Tyndall report derived 4.0 seconds from their study for the act of making a maneuver decision.

A.1.7 CA F7: Execute Maneuver

The Collision Avoidance System shall perform the commanded maneuver.

A.1.7.1 Maneuver Initiation Accuracy

The UA shall precisely execute the maneuver that was commanded.

A.1.7.2 UA Response Time

The UA shall initiate the commanded avoidance maneuver within TBD seconds of the pilot inputting the command.

Discussion/rationale: Normally, the aircraft will take approximately a second or two to begin responding after the pilot inputs the maneuver decision – this is known as "maneuver onset." This is based entirely on the responsiveness of the aircraft. In addition, the UAS communications link will introduce a slight delay. The Tyndall report derived 2.4 seconds from their study, although more time may be required for a UAS.

A.1.7.3 UA Response Characteristics

The UA response characteristics shall be an input to the CAS.

Discussion/rationale: This requirement deals with the UA flight characteristics. It is important that the UA be able to perform the commanded maneuver in a reasonable amount of time, and achieving the desired maneuver state quickly is the initial step. It is critical that the collision avoidance logic be calibrated to the responsiveness and maneuverability of the UA with which it is being used.

A.2 System Quality Guidelines

These guidelines govern the overall CA function, and recommend a level of quality that the system should meet in order to achieve its goal of avoiding collisions with cooperative aircraft. A more detailed explanation of these guidelines and rationale for the suggested values should be included in future revisions of this document.

A.2.1 System Continuity

The CA function shall have continuity similar to that of manned aircraft.

Note: Continuity addresses the end-to-end system functionality – the ability to be available when needed, and to provide continuous capability throughout a designated time frame.

A.2.1.1 Availability

The CA system shall have an availability that ensures a sufficient level of safety in the NAS.

Discussion: This parameter is related to reliability. The technical definition of availability is Operating Time/(Operating Time + Maintenance Down Time). On manned aircraft, a traffic detecting system such as TCAS is generally classified as essential (but not critical) equipment; a loss of its availability is defined by SAE ARP4761[25] as "Minor" on the Failure Condition Severity Classification scale. The associated probability of occurrence for this rating is 1×10^{-3} per flight hour, or one occurrence every 1000 hours. This requirement may be significantly stricter for a UA since there is no pilot performing the See & Avoid function.

A.2.1.2 Reliability

The CA system shall have a Mean Time Between Failures (MTBF) of 10,000 hours.

Discussion: The Mean Time Between Failures (MTBF) – the average number of hours a particular system will operate without a failure – determines the system's reliability. For those technologies that are still in early stages of development, engineering judgment is used based on similar technologies and concepts. The MTBF for an established system varies with its intended usage. For example, a commercial transport vehicle generally experiences relatively long cycle durations (3-10 hours), low vibration, and often has a temperature and humidity-controlled environment for its electronic devices. Thus, a TCAS box might be expected to last 20,000 hours between failures. A helicopter, on the other hand, presents much more demanding physical circumstances; a MTBF for the same component may be around 5,000 hours. Since a HALE UA is designed for extremely long cycle times (over 24 hours), but is small and susceptible to vibration, environment, and potential hard landings, it is expected that a MTBF of 10,000 hours is a reasonable preliminary estimate.

A.2.1.3 Operation during Maneuver

The performance of the CA subsystem shall not be adversely affected by forces generated during a maneuver, or the resultant change in UA attitude.

[25] SAE ARP4761 "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment", December 1996.

A.2.2 Operating Environment

The CA subsystem shall be able to function in all environmental conditions encountered during normal operation.

A.2.2.1 *Lighting Conditions*

The CA subsystem operation shall not be adversely affected by ambient lighting conditions, such as darkness or sun glint.

A.2.2.2 *Weather Conditions*

The CA subsystem shall be capable of operation in all normal weather conditions encountered, such as clouds and precipitation.

Discussion: The CA subsystem should be capable of detecting traffic in all VFR weather conditions at least as well as a human. However, according to FAR 91.113, the pilot of an aircraft is responsible for "see and avoid" whether they are operating under VFR or IFR.[26] Therefore, having the capability to detect other aircraft through various conditions (e.g. rain, fog, clouds) is still a requirement for UAS. This requirement does not take into account the environmental effects on the hardware itself, such as temperature and pressure of the compartment containing the CA hardware (see A.2.2.3).

A.2.2.3 *Other Environmental Conditions*

The CA subsystem hardware shall be able to withstand the range of interior temperatures, atmospheric pressures, humidity, and electromagnetic interference that can be expected during normal operation of all UAS elements.

A.2.3 System Integrity

The CA subsystem shall have an integrity value similar to the collision avoidance systems of manned aircraft, such as TCAS II. This is an indication of the system's ability to identify degraded input data or system functionality and continue sense and avoid operations within the limitations of the degraded system.

A.2.3.1 *Fault Detection*

The probability that a fault causing unsafe operation or lack of functionality will occur in the CA subsystem without notification to the UAS pilot shall be less than TBD.

A.2.3.2 *Fault Tolerance*

The CA subsystem shall fail-operate following a single failure, and fail-safe when unable to perform two or more subsystem functions.

Discussion/rationale: This guideline requires further discussion to ensure that it is not too strict.

[26] FAR 91.113, "*FAA Right of Way Rules*", Federal Aviation Regulations General Operating and Flight Rules

A.2.3.3 *False Alerts/Alarms*

The CA subsystem false alert/alarm rate shall be less than 2%.

Discussion/rationale: The NAS System Requirements document specifies a goal of no more than 2% nuisance alert rate and a threshold requirement of 6 percent for the air surveillance function of the NAS.[27]

A.2.4 System Interoperability

The UAS shall not cause performance degradation to any other system, external or internal to the UAS.

A.2.4.1 *UAS System Impact*

The CA subsystem shall not adversely affect any of the other UAS subsystems' abilities to perform their intended functions. This includes all components of the Air Vehicle Element, the Communications Element, and the Control Element.

A.2.4.2 *NAS Impact*

The CA subsystem shall burden the NAS no more than a typical manned aircraft. This includes interactions with ATC and other aircraft.

A.2.4.3 *Compatibility with Other Aircraft*

The CA subsystem shall be interoperable and suggest maneuvers that are compatible with the CA systems used on all aircraft that may be routinely encountered.

Note: This guideline is to ensure that all suggested collision avoidance maneuvers are compatible and/or coordinated with the threat.

A.2.4.4 *Detectability*

The UA shall be detectable by other traffic.

Note: Methods may include, but are not limited to the use of a transponder, high visibility paint, and lights.

A.2.5 System Certifications

The UAS shall have the appropriate certifications for its intended operational regime.

A.2.5.1 *Safety Certification*

The CA subsystem shall have a safety criticality certification of TBD, as defined in DO-178B.

A.2.5.2 *Software Certification*

The CA subsystem software shall be certified in accordance with DO-178B Level TBD.

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[27] FAA, NAS-SR-1000, NAS System Requirements, Change 10, Nov 1991.

A.2.5.3 Operational Maturity

The CA subsystem shall be certified to NASA TRL TBD or higher.

Discussion: This metric describes the level of development and testing that the system/technology has demonstrated. This metric also attempts to incorporate the certification of the system. The NASA Technology Readiness Level (TRL) is used to evaluate the parameter. Given the timetable of the Access 5 program, the minimum level to meet CA requirements is TRL 6, which corresponds to a technology flight demonstration.

APPENDIX B: VERIFICATION MATRIX

The five methods of requirements verification planned for Access 5 are:

- **Inspection/evaluation (I) –** Examination of equipment, drawings, or documentation.
- **Analysis (A) –** A method that utilizes established technical or mathematical algorithms, charts, graphs, circuit diagrams, or other scientific principles and procedures.
- **Simulation/modeling (S) –** The process of conducting experiments with a model. Simulation may include the use of analog or digital devices, laboratory models, or "testbed" sites.
- **Demonstration (D) –** A method that generally utilizes, under specific scenarios, the actual operation, adjustment, or reconfiguration of items.
- **Test (T) –** A method of verification that generally determines, quantitatively, the properties or elements of items, including functional operation, and involves the application of established scientific principles and procedures.

		Verification Method				
	Title	**I**	**A**	**S**	**D**	**T**
A.1	**Performance Guidelines**					
A.1.1	**CA F1: Detect Traffic**					
A.1.1.1	**Minimum Detect Time**			X	X	
A.1.1.2	**Detection Range**			X	X	
A.1.1.3	**Azimuth Field-of-Regard (FOR)**		X		X	
A.1.1.4	**Elevation Field-of-Regard**		X		X	
A.1.1.5	**Detection Probability**			X		
A.1.1.6	**Detection Rate**		X			
A.1.1.7	**Detection Accuracy**		X			
A.1.1.8	**False Detection/Nuisance**			X	X	
A.1.2	**CA F2: Track Traffic**					
A.1.2.1	**Tracking Surveillance Volume**		X		X	
A.1.2.2	**Simultaneous Track Capability**			X		
A.1.2.3	**Track Probability**			X	X	
A.1.2.4	**Track Quality**		X		X	
A.1.2.5	**Track Accuracy**		X		X	
A.1.2.6	**False Tracks**			X		
A.1.2.7	**Time to Establish Track**			X		
A.1.3	**CA F3: Evaluate Collision Potential**					
A.1.3.1	**Threat Evaluation**			X		
A.1.3.2	**Time to Classify Collision Potential**			X		
A.1.3.3	**Maneuver Completion**			X		
A.1.4	**CA F4: Prioritize Collision Threats**					
A.1.4.1	**Multiple Threat Prioritization**		X			
A.1.4.2	**Time to Prioritize Threats**			X		
A.1.5	**CA F5: Determine Avoidance Maneuver**					
A.1.5.1	**Recommended Maneuver**			X		

A.1.5.2	**Multiple Collision Threats/Induced Collision**			X		
A.1.5.3	**Unnecessary Evasion**		X			
A.1.5.4	**Adjust for Maneuver**			X		
A.1.5.5	**Time to Determine Maneuver**			X		
A.1.6	**CA F6: Command Maneuver**					
A.1.6.1	**Pilot Response Time**			X		
A.1.7	**CA F7: Execute Maneuver**					
A.1.7.1	**Maneuver Initiation Accuracy**			X	X	
A.1.7.2	**UA Response Time**			X		
A.1.7.3	**UA Response Characteristics**		X		X	
A.2	**System Quality Guidelines**					
A.2.1	**System Continuity**					
A.2.1.1	**Availability**		X			
A.2.1.2	**Reliability**		X			
A.2.1.3	**Operation during Maneuver**		X			
A.2.2	**Operating Environment**					
A.2.2.1	**Lighting Conditions**					X
A.2.2.2	**Weather Conditions**					X
A.2.2.3	**Other Environmental Conditions**					X
A.2.3	**System Integrity**					
A.2.3.1	**Fault Detection**		X		X	
A.2.3.2	**Fault Tolerance**		X			
A.2.3.3	**False Alerts/Alarms**		X			
A.2.4	**System Interoperability**					
A.2.4.1	**UAS System Impact**		X			
A.2.4.2	**NAS Impact**		X		X	
A.2.4.3	**Compatibility with Other Aircraft**	X			X	
A.2.4.4	**Detectability**	X				
A.2.5	**System Certifications**					
A.2.5.1	**Safety Certification**		X			
A.2.5.2	**Software Certification**		X			
A.2.5.3	**Operational Maturity**	X				

APPENDIX C: FUNCTIONAL REQUIREMENTS TRADE-OFF ANALYSIS

C.1 Introduction

The framework for UAS sense and avoid is comprised of six basic functions derived from the human model for mid-air collision avoidance. These steps involve: 1) scanning the surrounding airspace for other aircraft, 2) tracking any detected traffic, 3) determining if the detected aircraft is on a collision trajectory, 4) deciding what evasive maneuver must be performed, if any, 5) initiating the appropriate maneuver and 6) assessing if the maneuver was effective. Each of these functions cannot, however, be evaluated in isolation. This appendix begins to address trade-offs by presenting examples of the analysis required for future platform designs in order to make decisions on vehicle maneuverability, sensor capability, and data processing requirements.

C.2 Purpose

The purpose of this analysis is to supplement the functional requirements that have been identified in this document. Most of the functional requirements have been written to allow the UAS designers and manufacturers some flexibility in how they achieve an equivalent level of safety and perform the six collision avoidance steps listed above. However, the following graphs and tables attempt to provide a frame of reference for several example collision threat scenarios. Hopefully, this will provide some insight into the kind of trade-offs that can be made with certain design qualities of a UA. For example, a highly maneuverable UA will require less distance from a conflicting aircraft at the initiation of the avoidance maneuver due to its higher turn rate and climb/dive rates.

C.3 Model Description

The data presented in this appendix was generated with an EXCEL-based encounter model developed by Modern Technology Solutions, Incorporated (MTSI) to examine potential collision scenarios between two aircraft. The model uses simplified flight path calculations based on aircraft bank angle and velocity to determine the closest point of approach for a given set of starting conditions. In an iterative mode, the model can be used to vary input parameters over a desired range to generate a set of curves showing the minimum distance necessary between aircraft at the beginning of an avoidance maneuver to achieve a desired miss distance. The avoidance maneuver can be either a climb/dive action or a change in heading.

C.4 Model Assumptions and Inputs

Each encounter is modeled by establishing the initial conditions for both aircraft, positions relative to the potential impact point using aircraft bearing and separation distance, and UA maneuver parameters as shown in Figure 1. For this analysis, the conflicting aircraft was assumed to be non-maneuvering. Given the initial conditions, the model determines the closest point of approach by calculating relative positions as the scenario runs until the separation distance begins to increase. At the initiation of the scenario, the UA is assumed to roll instantaneously to the bank angle necessary to achieve the required turn rate until reaching the heading change input value. Similarly, when a climb/dive maneuver is initiated, the desired rate is achieved instantaneously and maintained until the altitude change is completed.

When the model is used in the iterative mode, the primary output is a report of the minimum distance required between the aircraft at the initiation of the avoidance maneuver to ensure the required miss distance is not penetrated. This mode provided the best method for studying the functional requirement trade-offs. Although this model helped develop better understanding of the encounter geometry and critical factors, all data should be considered notional because of the simplifying assumptions applied to UA maneuvering.

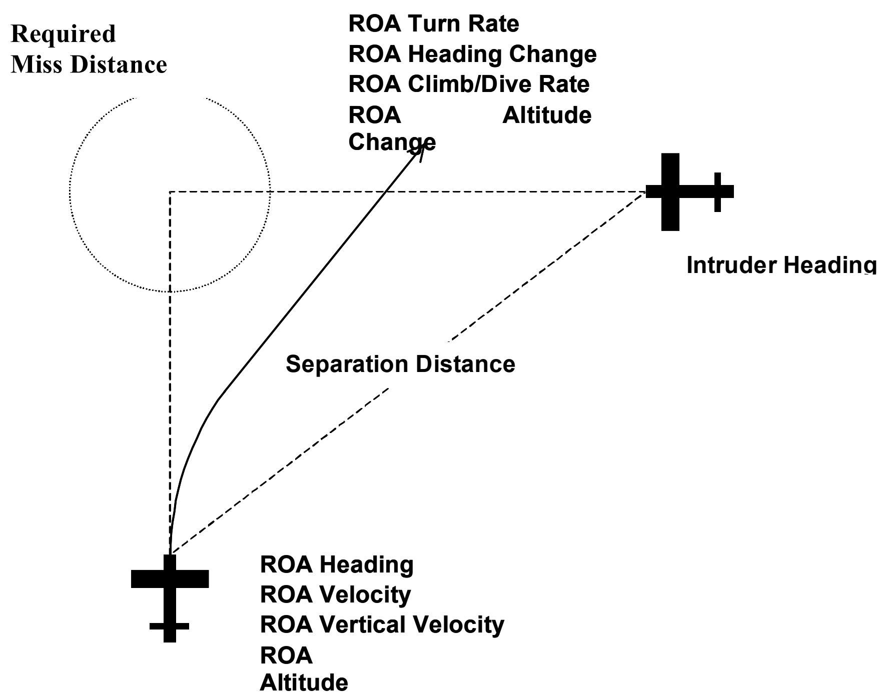

Figure 1: Model Input Variables

C.5 Minimum maneuver distance/time results

The results in this section demonstrate trade-offs between UA maneuverability and the minimum distance between aircraft for initiation of an avoidance maneuver to maintain the indicated miss distance. Figure 2 can be used for all results to convert from turn rate to UA bank angle.

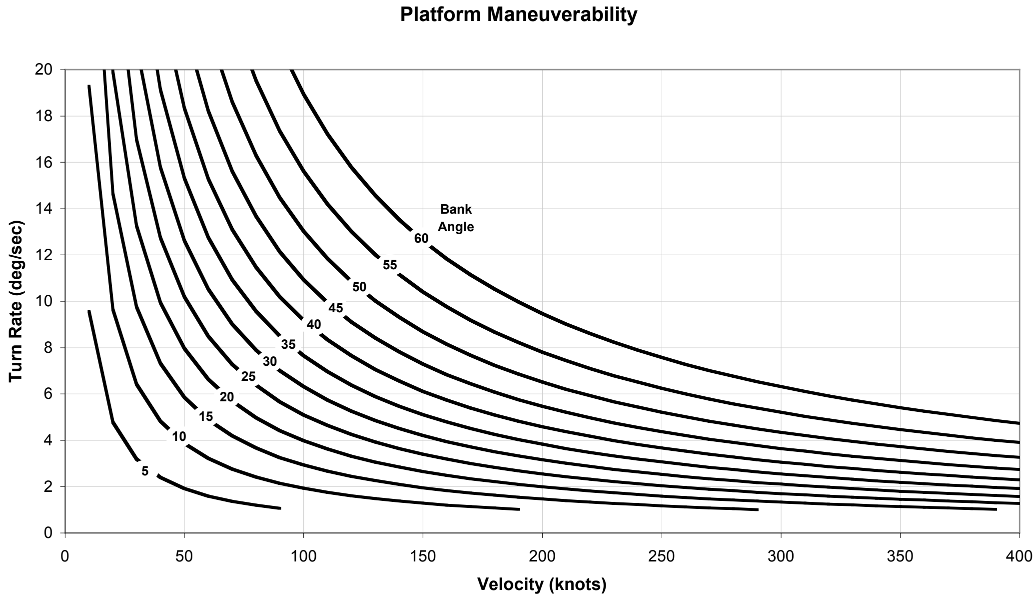

Figure 2: Platform Maneuverability

C.5.1 Horizontal Maneuver

Several scenarios were run to gain a better understanding of the impact of UA and intruder velocity on the Minimum Maneuver Distance (distance between aircraft at the initiation of the avoidance maneuver) required to maintain a series of required miss distances (100-1000 ft). The first scenario examined was a head-on encounter with the encounter parameters in Figure 3.

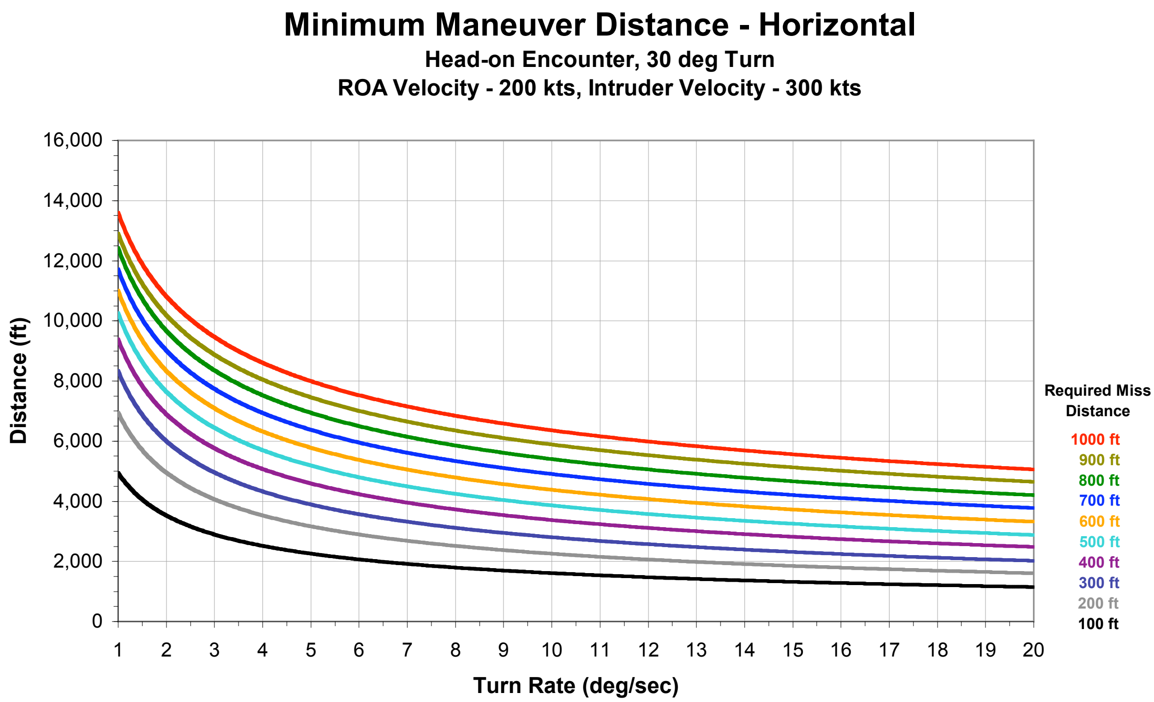

Figure 3: Minimum Maneuver Distance - Head-On

Table 1 uses the required maneuver distance for a UA flying at 200 kts and applies a range of detection processing times to show how the required distance varies with intruder velocity for a 500 ft required miss distance.

Required Detection Range (ft)

	Detection Processing (sec)			
Intruder Velocity	**10**	**20**	**30**	**40**
200 kts	13,426	21,856	30,286	38,716
250 kts	14,126	22,556	30,986	39,416
300 kts	14,675	23,105	31,535	39,965
350 kts	15,299	23,729	32,159	40,589
400 kts	16,025	24,455	32,885	41,315

Table 1: Required Detection Range – Horizontal Maneuver

Figure 4 shows how the **Minimum Maneuver Distance** varies with changes in the UA and intruder aircraft velocities.

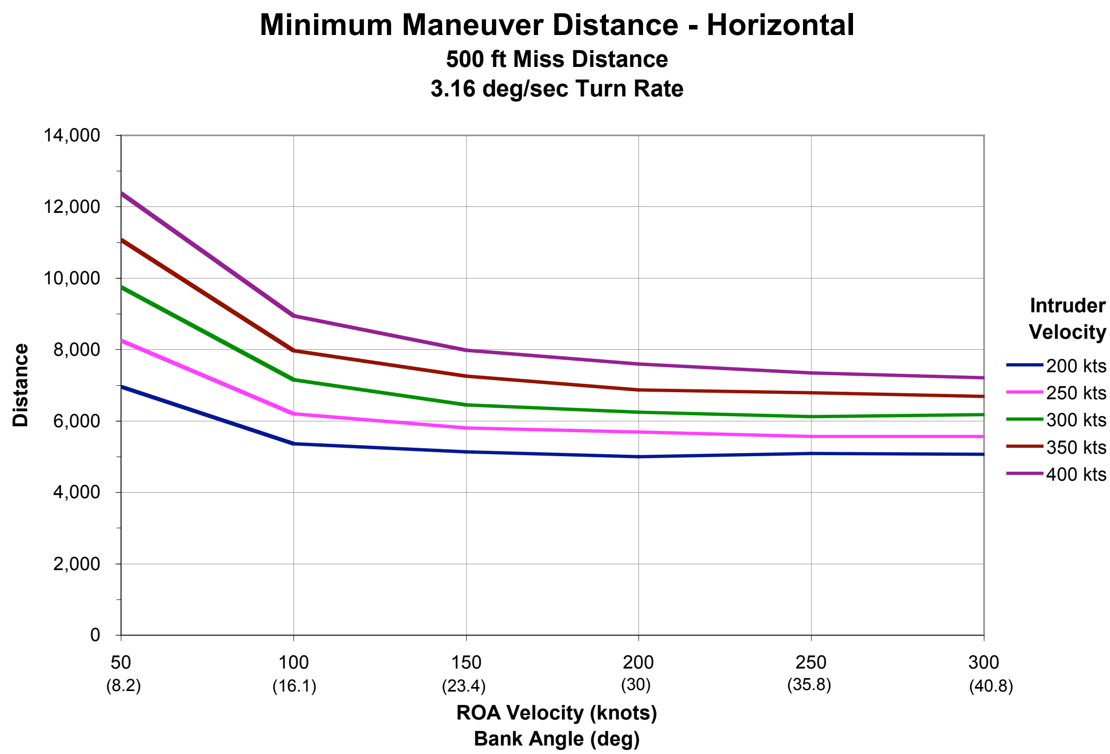

Figure 4: Minimum Horizontal Maneuver Distance - Velocity Impact

The previous data are all based on a head-on encounter. The effect of encounter geometry is examined in Figure 5 by utilizing the same UA input conditions as in Figure 3, but with an intruder aircraft closing from 60^{o} off the nose of the UA.

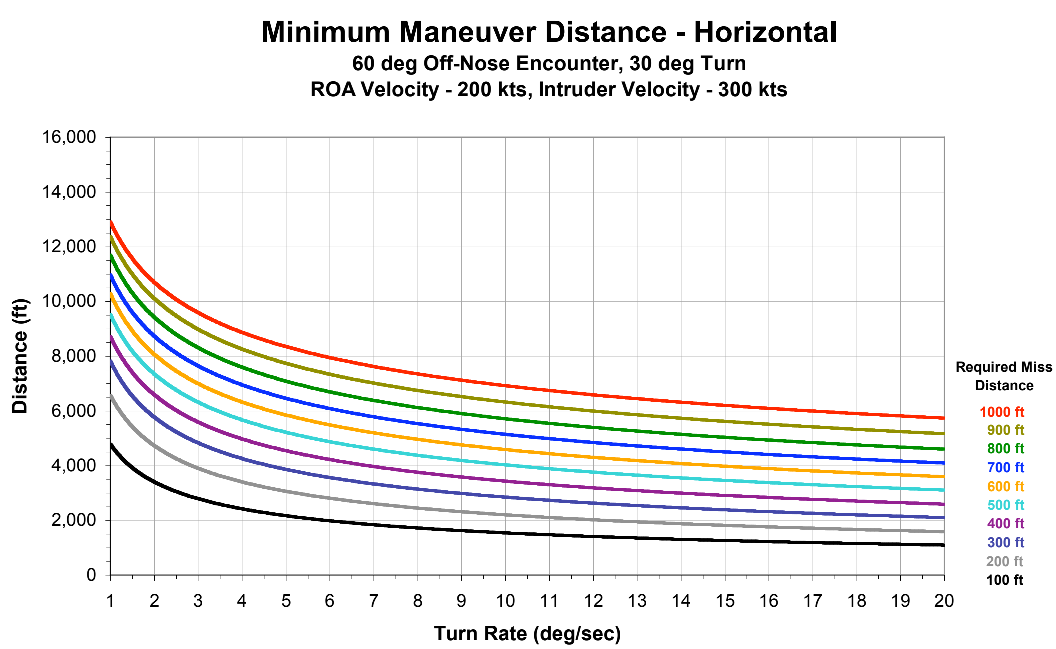

Figure 5: Minimum Maneuver Distance - 60 degrees Off Nose

Finally, Figure 6 shows the Minimum Maneuver Distance data from Figure 3 plotted in terms of the time to impact.

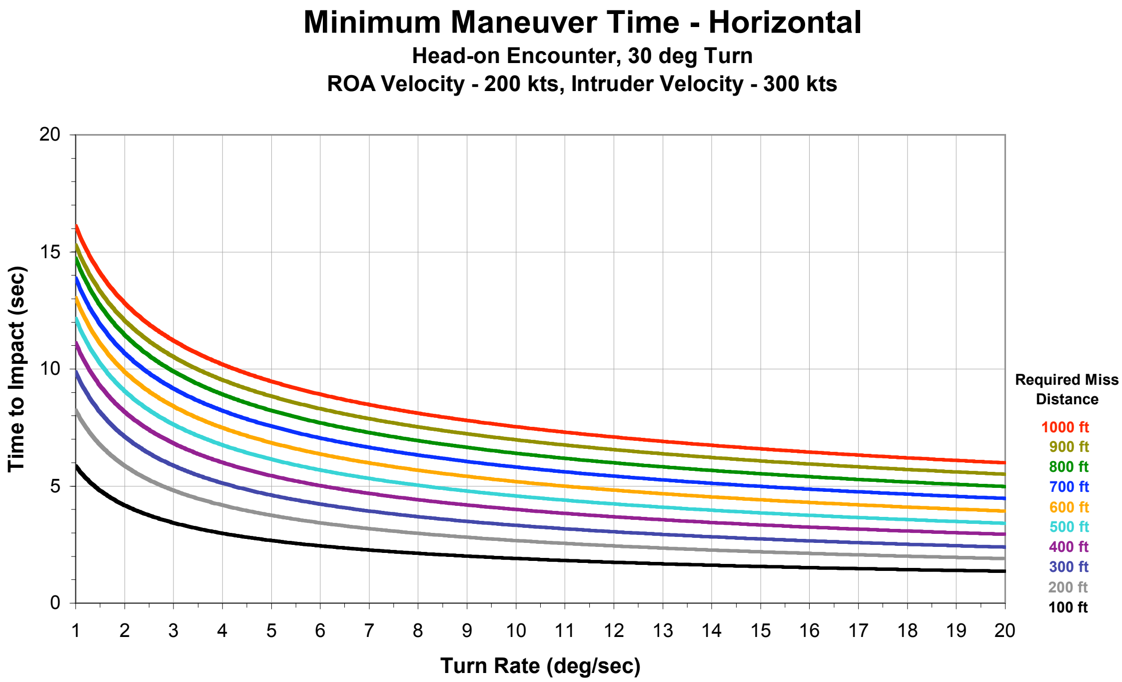

Figure 6: Minimum Maneuver Time - Head-On

C.5.2 Vertical Maneuver

Vertical avoidance maneuvers must also be examined in addition to horizontal. Figure 7 depicts the maneuver and input parameters. As with horizontal maneuver scenarios, the intruder aircraft is assumed to be non-maneuvering. Unlike the horizontal maneuver, however, there is no turn radius associated with the change in vertical velocity. The change is assumed to be instantaneous at the beginning of the avoidance maneuver.

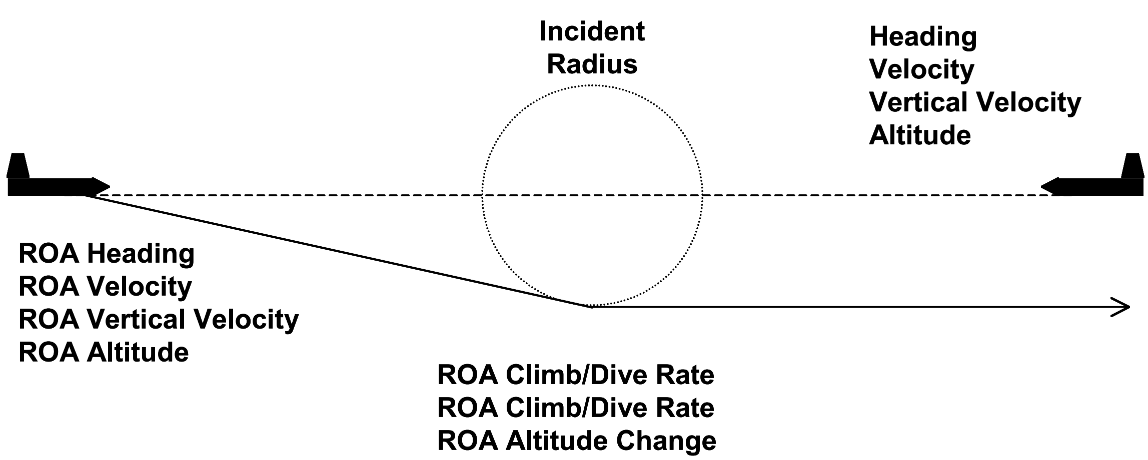

Figure 7: Vertical Avoidance Maneuver

For an intruder aircraft at the same altitude as the UA, results are shown in Figure 8 for a series of UA vertical velocities and required miss distances. In addition to the assumption that the UA instantaneously assumes the desired climb/dive rate when the maneuver is initiated, both aircraft maintain a constant velocity throughout the scenario.

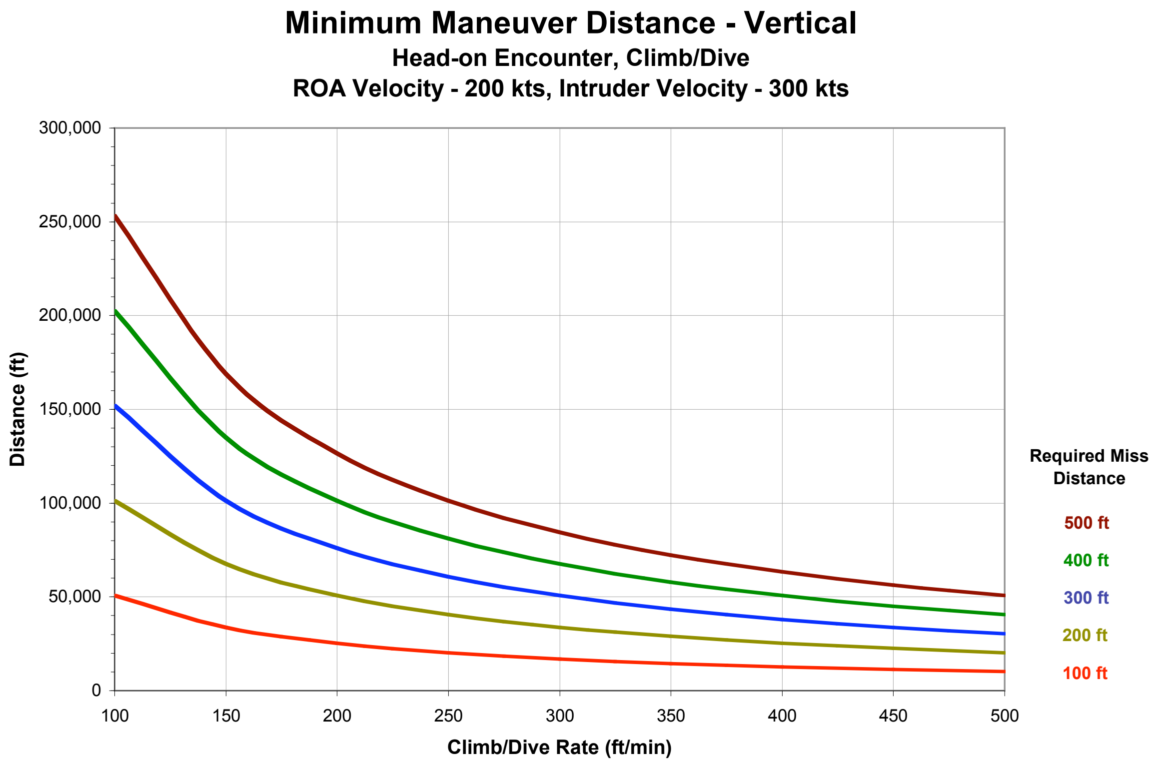

Figure 8: Required Maneuver Distance – Vertical

Table 2 results from applying the same detection processing times used in the horizontal maneuver analysis to a vertical avoidance scenario with the UA at 200 kts, intruder aircraft at 300 kts and a 200 ft/min vertical velocity to achieve a 100 ft miss distance.

Required Detection Range (ft)

	Detection Processing (sec)			
Intruder Velocity	**10**	**20**	**30**	**40**
200 kts	27,004	33,756	40,507	47,258
250 kts	30,380	37,975	45,570	53,165
300 kts	33,756	42,194	50,633	59,072
350 kts	37,131	46,414	55,697	64,979
400 kts	40,507	50,633	60,760	70,887

Table 2: Required Detection Range – Vertical

Figure 9 shows how the required maneuver distance increases with higher closing velocities for a relatively low vertical velocity. In this case, it takes 150 seconds for the UA to change altitude by 500 ft with a 200 ft/min vertical velocity. If both aircraft are flying at 200 kts (337 ft/sec), the distance traveled by both aircraft is over 16 nm.

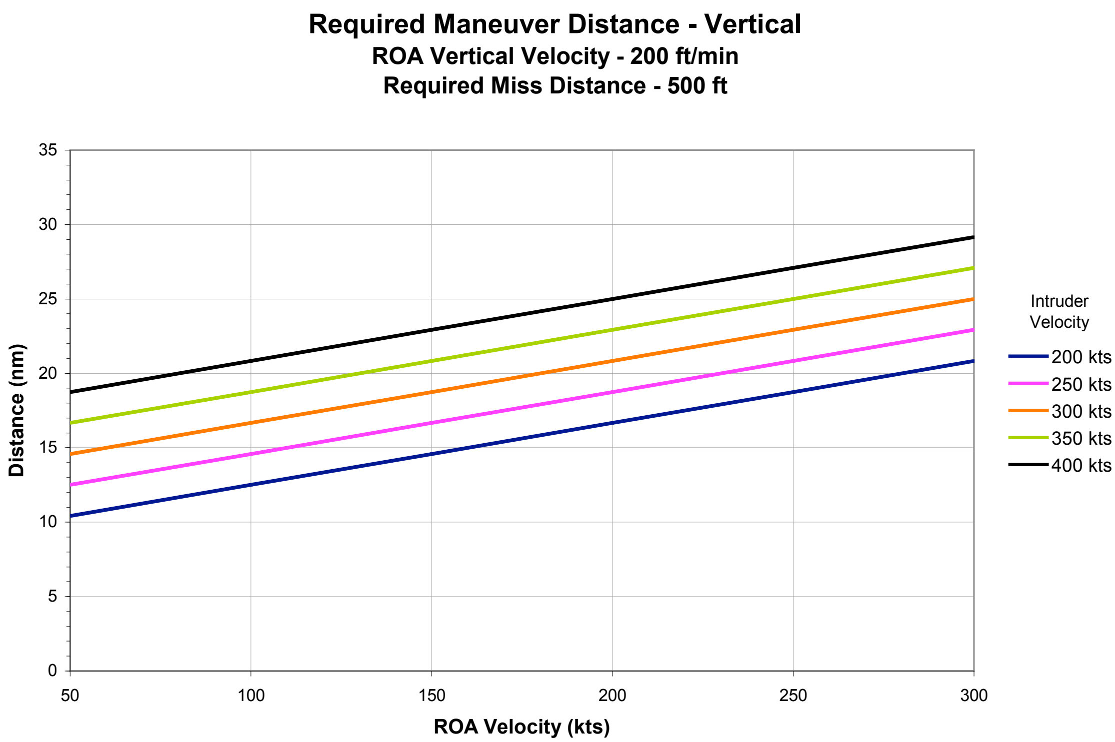

Figure 9: Minimum Maneuver Distance – Velocity Impact