FAA/AFS-407

Evaluation of Candidate Functions
for
Traffic Alert and Collision Avoidance System II (TCAS II)
On
Unmanned Aircraft System (UAS)

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Executive Summary

There has been a substantial debate regarding the use of the Traffic Alert and Collision Avoidance System (TCAS) on Unmanned Aircraft Systems (UAS). Advocates for the installation and use of TCAS on UAS have proposed that the system could benefit UAS pilots in providing a means to maneuver around potentially conflicting traffic. The TCAS traffic display has also been proposed to provide general awareness of the traffic environment around the aircraft because the pilot lacks a means to visually acquire and monitor aircraft operating in the vicinity of the UA.

TCAS is a family of airborne devices that function independently of the ground-based air traffic control (ATC) system, and provide collision avoidance protection for a broad spectrum of aircraft types. All TCAS systems provide some degree of collision threat alerting, and a traffic display. TCAS I and II differ primarily by their alerting capability. TCAS I provides Traffic Advisories (TAs) to assist the pilot in the visual acquisition of intruder aircraft. TCAS II provides TAs and Resolution Advisories (RAs), i.e., recommended escape maneuvers, in the vertical dimension to either increase or maintain the existing vertical separation between aircraft.

The Federal Aviation Administration (FAA) has historically discouraged the use of TCAS on UAS for several reasons:

- TCAS II is only required, by regulation, for turbine aircraft, greater than 33,000 lb maximum take off weight, involved in air commerce operating under Title 14 Code of Federal Regulations (14CFR) Part 121, 125 or 129
- TCAS II was not designed for installation on UAS; it is intended to be installed on large commercial transport category, turbine powered aircraft as a last resort collision avoidance system
- Other manned aircraft may install TCAS II, but must meet the installed minimum performance required in TSO-C119 and comply with certain airworthiness provisions of 14 CFR
- TCAS I is only required for general aviation aircraft involved in air commerce operating under 14CFR Part 135
- The TCAS traffic display (TCAS I or TCAS II) is primarily intended to assist the pilot in visually acquiring traffic for exercising see and avoid; its design and limitations are only supplemental to the pilot in visual acquisition
- Maneuvering solely on the basis of TCAS traffic symbology is explicitly prohibited as part of its existing operational approval
- The TCAS minimum performance specification does not provide for a distributed architecture, implemented over a data link, which would be needed if TCAS is employed on a UAS
- The TCAS system is not a means of compliance, or partial compliance, with operational rules to see and avoid or remain well clear of other aircraft
- There has been no rigorous safety analysis of any proposed use of TCAS on UAS

The FAA Unmanned Aircraft Program Office chartered an effort to identify and analyze potential methods of use for TCAS on UAS to establish the basis for policy and guidance. The evaluation identified three (3) candidate functions:

- Self Separation
- Collision Avoidance
- Situation Awareness

It was determined that these "candidate functions" required developing a more structured approach for specifying the functions and the various ways they might be implemented. Therefore, it was resolved, as a matter of convention, that the potential uses of TCAS considered for analysis were more accurately described as "methods" for accomplishing one of the three candidate functions.

Three (3) methods were chosen for analysis because they were determined to have the most potential benefit for a UAS, balanced against the time and resources required to develop and analyze them.   None of the methods that implement the Collision Avoidance function were selected for analysis as they were determined to be the least likely to result in an acceptable level of risk. An implementation to comply with TCAS II Resolution Advisories was also deferred for analysis as it necessitates an exhaustive assessment of the system from requirements definition to a system safety assessment of the architecture (including the UAS pilot). Lastly, the methods selected for analysis were thought to be the most highly desired by the UAS community. The methods selected for analysis were:

- Use of the TCAS display to make a vertical maneuver against a single threat aircraft for the intended function of self separation
- Use of the TCAS display to make a horizontal maneuver against a single threat aircraft for the intended function of self separation
- Use the TCAS display for the intended function of situation awareness

These methods were evaluated using a Preliminary Hazard Analysis (PHA) which examined the selected methods using a disciplined process of hazard identification, contributing causes and their potential effects in the National Airspace System (NAS). The PHA followed the process contained in the FAA System Safety Risk Management (SMS) manual.

The study concluded the installation and use of TCAS on UAS should not be authorized for:

- Performing a horizontal maneuver using the TCAS traffic display for self separation, and is unsafe in Class A, B, C, D, E, and G airspace
- Performing a vertical maneuver using the TCAS traffic display for self separation, and is unsafe in Class A, B, C, D, E, and G airspace

- Situational awareness as a basis for maneuvering is unsafe as the representation of the traffic situation is inaccurate, potentially incomplete, and misleading for maneuvering decisions

The analyses were predicated on several governing assumptions, including: TCAS installations would meet the minimum performance specifications of their respective Technical Standard Orders (TSO), TCAS installation would be certified by applicable airworthiness certification authorities, UAS would not automatically (or autonomously) respond to any TCAS derived traffic information.

The installation and use of TCAS II in accordance with TSO-C119, "Traffic Alert and Collision Avoidance System (TCAS) II, Airborne Equipment (TCAS II)" is conceivable, but would require that a complete assessment of the system be conducted to demonstrate that it meets the installed minimum performance requirements specified in the TSO. A substantiating analysis must also address the safety critical functions implemented in data link architecture with appropriate compensating provisions to address the removal of the pilot from the aircraft and thus would require another means to identify situations where compliance with RA guidance would be unsafe.

It is further recognized that TCAS could be integrated, in total or in part, as a component in a proposed Sense and Avoid system, but further study would be required to define architectures suitable to UAS design limitations and to validate its allocation in such architectures by applicable system safety assessments.

1 Introduction

The Traffic Alert and Collision Avoidance System II (TCAS II) was developed as a last resort airborne collision avoidance system. The system provides pilots with vertical maneuvering guidance to increase vertical separation between two (or more) aircraft when the TCAS processor determines an approaching aircraft poses a collision threat. TCAS II includes a traffic display to provide:

- An aid to visual acquisition to cue pilots about potentially conflicting traffic
    - Objective is to assist in visually acquiring conflicting traffic for exercising see and avoid responsibility prior to the issuance of a Resolution Advisory (RA)
- Visual alert to the pilot to prepare for responding to a potential RA
- Provide situation awareness
- An increase in pilot and controller confidence in the TCAS system

The TCAS system tracks aircraft equipped with airborne transponder equipment and provides Traffic Alerts (TA) when aircraft are in close proximity. The system includes a traffic display designed to cue pilots where to look out the window to visually acquire potentially conflicting airborne traffic in order to see and avoid them. The TCAS II system also provides RAs, i.e., recommended escape maneuvers, in the vertical dimension to either increase or maintain the existing vertical separation between aircraft.

Other traffic advisory systems (e.g. TCAS I, Traffic Information Service, etc.) may also employ a traffic display and alerting to increase the chances of the pilot visually acquiring potentially conflicting traffic, but are generally lower fidelity systems compared to TCAS II. TCAS II is the only system which provides RAs and has a larger surveillance range and higher performance than other traffic information systems. Use of these other traffic advisory/information systems on an UAS is not addressed in this report. Hereafter "TCAS" will be used to refer to TCAS II unless a different reference is specifically required by the context in which it is used. See 5Appendix D for a more detailed description of TCAS II.

The installation and use of the TCAS on UAS has been a topic of substantial debate and deliberation. The impetus for the use of TCAS on UAS is believed to have stemmed from regulatory equipage requirements for TCAS II on passenger and cargo aircraft under Title 14 Code of Federal Regulations (14CFR) Part 121, §121.356 and 14CFR Part 129, §129.18 respectively. Aircraft operating under these regulations are subject to TCAS equipage requirements based on the number of passenger seats, or in the case of cargo aircraft, the maximum certificated take-off weight. The ultimate objective was to make UAS acceptable to operate in the National Airspace System (NAS) which was interpreted to include TCAS equipage. There was also a desire to provide traffic Situation Awareness to UAS pilots. Proponents often assert that installation of TCAS will facilitate obtaining unrestricted access to the NAS for UAS so equipped.

The Federal Aviation Administration (FAA) has historically discouraged the use of TCAS on unmanned platforms, not only on technical and operational grounds, but also because a satisfactory rationale, as part of a formal safety case was never presented for its proposed use and intended function as installed on a UAS.

To that end, the FAA Unmanned Aircraft Program Office (UAPO) established a team to evaluate potential uses of TCAS on Unmanned Aircraft (UA). This includes possible "alternative" uses of TCAS, different from its certificated intended function and associated operational approval for use on manned aircraft, by developing rational concepts of operation and assessing their feasibility when employed on a UAS and the safety impact to the NAS

1.1 Background and Motivation

There have been suggestions that UAS could benefit from the installation of TCAS. Notwithstanding the limited data provided to the pilot and inaccuracies of traffic information presented on the TCAS traffic display, debate has persisted about its value and efficacy as a decision support tool for a UAS pilot lacking any other information about traffic in the vicinity of the UA.

Although efforts are underway to define System Requirements and Minimum Performance Standards for Sense and Avoid (SAA) equipment for UAS, these efforts are in their early stages of requirements definition with completion schedule estimates beyond 2015. As a critical element for integration of UAS into the NAS, the timelines are perceived by the user community to be too long to meet the demand for routine airspace access.

TCAS has proven to be an effective safety system in the NAS today for providing pilots with traffic information and collision avoidance protection from appropriately equipped aircraft.

It's important to note that the TCAS system was designed to work even when the Air Traffic Control (ATC) system has failed in some way. In other words, its design is as *independent* as possible from the ATC system, sharing only the airborne transponder as a means to detect and track aircraft, with the added benefit of helping the pilots look out the window to see nearby aircraft to avoid them.

Given the safety record of TCAS since its deployment in 1990 and that it has a traffic display to help pilots see and avoid, it's understandable why some would quickly jump to the conclusion that installing it on a UAS would be a good thing to do in terms of safety. It is particularly important to note that in manned aircraft, pilots maintain situation awareness and continue to use good operating practices and judgment when following TCAS RAs.

In manned aircraft, pilots are expected to maintain frequent outside visual scan, use see and avoid vigilance, and continue to communicate as needed and as appropriate with ATC.[1] The key distinction is that pilots use TCAS traffic display information as an *aid to visual acquisition* supporting their responsibility to see and avoid as opposed to its proposed use on UAS as a *replacement* for see and avoid. Using TCAS is inadequate as the sole source of traffic information to create situation awareness. Absent any additional information, the TCAS traffic display becomes a compelling representation of the surrounding airspace in an environment lacking other traffic information tools, with no way of verifying that the perceived "truth" is in-fact, a complete and accurate representation of actual traffic locations.

Although the incompatibilities of TCAS on a UAS can be identified through a review of the design assumptions, intended function, and failure condition classification of TCAS, there has not been a disciplined operational and technical assessment to identify risks of installing TCAS on UAS for any intended function.

To address this concern, an effort was initiated by the FAA UAPO to identify candidate intended functions of TCAS on UAS, evaluate the hazards exposed by its use and attempt to develop appropriate operational or technical mitigations to control those hazards so that some benefit might be derived from its use. The following sections outline the process for conducting these assessments.

1.2 Scope

This evaluation is intended to answer fundamental questions about the use of TCAS on UAS and its ability to provide self separation, collision avoidance and situation awareness for UAS operating in the NAS. The desire of many organizations, both public and civil, to use TCAS on UAS in a manner other than its intended function, has led to the formation of this working group to investigate and analyze candidate functions and methods to implement those functions. These are considered potential uses of TCAS and its traffic display, which are an extension beyond the existing certificated intended function.

The evaluation includes an assessment of the functionality that would be obtained by installing and using TCAS on a UAS. This was accomplished by conducting an assessment of the candidate functions and methods to implement those functions, using a disciplined safety process, to identify hazards, causes and potential effects on the NAS. Specific actions or decisions a pilot or electronic observer might make, based on the TCAS traffic display, are proposed as part of the process with limitations imposed to mitigate operational hazards where appropriate.

[1] Introduction to TCAS II, Version 7

This evaluation appraises the risk of using the existing TCAS equipment and displays in a manner other than as intended and designed. The design is specified in Technical Standard Order (TSO) C-119c, installed in accordance with Advisory Circular (AC) 20-151A and used in accordance with the standard published operating procedures in AC 120-55B.

Time is a critical aspect of the TCAS design, not only the time from intruder detection, the establishment of tracks and presentation on the traffic display, but also in the timing of the pilot response to alerts and interpretation of the traffic display. Pilot responses are largely influenced by the visual presentation of aircraft flight displays and the control interface in the UAS control station. Time delays inherent in UAS operations (both data link latency and the pilot response delay) add complexity to TCAS installation and use on UAS that are not a factor for TCAS on a traditional manned aircraft. Latency, when used in this document, refers to this end-to-end time delay to include data link and pilot response time delays, unless otherwise specified.

Current UAS datalink architectures and pilot interfaces are not standardized such that assumptions on their latencies and response delays could be included in these analyses and are considered beyond the scope of this study. Therefore, the timing requirements specified in the TCAS Minimum Operational Performance Standard (MOPS) is assumed for the purpose of this study and its supporting analyses.

1.3 Objectives

This evaluation is intended to identify any potential uses that may warrant a full scale evaluation by a Safety Risk Management Panel and to provide the basis for establishing FAA policy on the installation and use of TCAS on UAS.

This report on the evaluation process provides the following:

- Listing of candidate function uses of TCAS on UAS for analysis
- Listing of new methods for TCAS on UAS to meet the intent for the new candidate functions
- Selection of methods for analysis and supporting rationale
- Presents the evaluation/analysis approach for evaluating those new methods
- Describes a concept of operations for using TCAS with select new methods
- Provide Preliminary Hazard Assessment (PHA) for using TCAS with select new methods
- Recommend follow on work

The results of these concepts and evaluations provide recommendations for further research and development to investigate possible changes to TCAS such that it could be used on UAS. This evaluation recommends future work including flight testing, modeling/simulation or analysis to validate accepted concepts and their underlying assumptions, or potential changes to TCAS logic to accommodate unique characteristics of UAS.

1.4 Assumptions

Several assumptions were identified and documented while developing the candidate functions and new methods and also while performing the assessments.

1. Only collision avoidance equipment meeting TSO-C119c will be installed in the UAS.
2. The TCAS installation will be in accordance with AC 20-151A, Airworthiness Approval of Traffic Alert and Collision Avoidance Systems (TCAS II), Versions 7.0 & 7.1 and Associated Mode S Transponders or AC 20-131A, Airworthiness Approval of Traffic Alert And Collision Avoidance Systems (TCAS II), and Associated Mode S Transponders.
3. All public and civil UAS will go through an appropriate airworthiness approval process for the installation of TCAS and request operational approval for the use of the equipment for its proposed function.
4. The pilot (or other third party observer to interpret the display) will be adequately trained, qualified and approved for interpreting the display of traffic information.
5. ATC personnel will be trained in the type and characteristics of the UAS being flown in addition to the procedures pilots would employ for maneuvering.
6. The display will be in continuous display mode for the candidate functions.
7. UAS will have no restrictions in terms of airspace access, daylight vs. night flight operations, etc.
8. TCAS information is sent across data link to the UAS pilot/operator (e.g. traffic information)
9. UA does not autonomously maneuver on TCAS outputs (this behavior is out of scope)
10. All air traffic is following the applicable regulatory requirements and rules of the air
11. Appropriate cautions and warnings are placarded to the display to specify limitations and inaccuracies of the presented traffic information
12. UAS is capable of displaying and transmitting pressure altitude (not GPS only)
13. There is an integrity verification on the UAS pressure altitude data
14. No mitigation credit is given for the intruding aircraft seeing and avoiding the UA during an encounter
15. No mitigation credit is given for the intruding aircraft having TCAS RA protection against the UA during an encounter

1.5 Definitions

For this report the following words are defined as;

Table 1 Definitions

Air Traffic Control Services	A service provided for the purpose of:[2] 1. Preventing collisions: a. Between aircraft; and b. On the maneuvering area between aircraft and obstacles. 2. Expediting and maintaining an orderly flow of air traffic.
Collision Avoidance	The action, independent of ATC separation services, where a UAS maneuvers to prevent penetration of the collision volume.[3]
Collision Volume	A cylindrical volume of airspace centered on the UA with a horizontal radius of 500 ft and a vertical height of 200 ft (± 100 ft)[4] within which avoidance of a collision can only be considered a matter of chance.[5]
Encounter	The interval of time that any intruder remains on the TCAS display and the pilot performs state estimates and trajectory projections with respect to ownship.
Intruder	A transponder equipped aircraft within the surveillance range of TCAS for which TCAS has an established track.[6]
Pilot Determined Threat	Any intruder on the TCAS display which causes the UAS pilot a higher level of concern due to the perceived or actual loss of self separation or mid-air collision risk - either present or anticipated.
Self Separation	The action independent of ATC separation services where a UAS maneuvers to maintaining well clear, while conforming to accepted right of way rules.[7]
Separation	The spacing of aircraft to achieve their safe and orderly movement in flight and while landing and taking off.[8]
Service	A generic term that designates functions or assistance available

[2] FAA Order 7110.65T, PCG A-5

[3] SAA Workshop Final Report

[4] DO-185B, Section 1.8, Glossary of terms

[5] DO-298, Appendix E 1.2

[6] DO-185B, Section 1.8, Glossary of terms

[7] SAA Workshop Final Report

[8] FAA Order 7110.65T Pilot/Controller Glossary

	from or rendered by ATC.[9]
Situation Awareness	The perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future.[10] NOTE: Situation Awareness is also commonly referred to as "Situational" Awareness; however, Endsley's terminology and definition is widely accepted in the formal study and analysis in the field of Human Factors engineering. Although Endsley's terminology is used in this paper and associated analyses, the two terms are used interchangeably.
Threat	A target that has satisfied the threat detection logic and thus requires a resolution advisory.[11]
Traffic	Any detected or undetected aircraft in the vicinity of the UAS.
Well Clear	The state of being able to maintain a safe distance from other aircraft so as not to cause the initiation of a collision avoidance maneuver in either aircraft.[12]

2 Evaluation

This report evaluates the use of TCAS on a UAS, first by identifying candidate functions and methods, then by assessing their risk. Section 2.1 describes the selection of candidate functions and methods for its use. The process for evaluating the candidate functions is provided in section 2.1.3. The process flow is described in section 2.2 with a description of the pilot's decision process. The intended use for each of the functions and methods is contained in section 2.3 & 2.4 and section 2.5 describes the hazard assessment. The decision criteria are explained in section 2.6.

2.1 Functions and Methods

Twelve (12) potential methods for the use of TCAS on UAS were initially considered for evaluation based on proposed functions that various UAS operators suggested. These potential uses were outlined in an interim report which was published in October 2009 and described as "candidate functions" therein.

Subsequent to the publication of the interim report, it was determined that the categorization of these "candidate functions" required developing a more structured approach for specifying the functions and the various ways the functions might be implemented. The importance of accurately describing the candidate functions and the

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[9] FAA Order 7110.65T

[10] Mica R. Endsley, "Design and Evaluation for Situation Awareness Enhancement"

[11] DO-185B, Section 1.8, Glossary of terms

[12] SAA Workshop Final Report

methods to implement them became critical in structuring the analyses and for referring to the functions and their respective "methods" of implementation. Therefore, it was resolved, as a matter of convention, that the potential uses of TCAS considered for analysis were more accurately described as "methods" for accomplishing one of the following three (3) candidate functions:

1. Collision Avoidance
2. Self-Separation
3. Situation Awareness

Methods, for the purposes of this report and its supporting analyses, are defined as conceptual uses of TCAS (including displayed traffic information) supporting decisions and any resulting actions to accomplish one of these three (3) candidate functions.

The original list of candidate functions described in the interim report (6.1-6.12) was changed to match the candidate functions and their methods used in this report. Two additional methods, horizontal and vertical maneuvers, were identified where the pilot would maneuver the UAS to avoid TA traffic symbology on the traffic display and considered methods to achieve the Collision Avoidance candidate function (2.1.1 methods 1.a and 1.b).

2.1.1 Candidate Methods

Several candidate methods were considered for evaluation using a PHA methodology as detailed in section 2.5. The candidate methods are associated with the candidate functions as follows:

1. Collision Avoidance
    a. Vertical maneuver to avoid intruders depicted as a TA on the TCAS traffic display
    b. Horizontal maneuver to avoid intruders depicted as a TA on the TCAS traffic display
    c. Maneuver in response to a TCAS Resolution Advisory
2. Self-Separation
    a. Vertical maneuver to remain well clear from intruders depicted as proximate traffic or other traffic on the TCAS traffic display
    b. Horizontal maneuver to remain well clear from intruders depicted as proximate traffic or other traffic on the TCAS traffic display
    c. Speed change maneuver to remain well clear from intruders depicted as proximate traffic or other traffic on the TCAS traffic display
    d. Maneuver to resolve multiple simultaneous threat aircraft
    e. Maneuver to sequence into the traffic pattern at uncontrolled airport (no ATC delegation)
    f. Perform delegated separation similar to visual separation procedures
    g. Stay in a "dark area" of the display by maneuvering away from traffic displayed in a particular quadrant of the display

3. Situation Awareness
    a. Use of TCAS traffic display to provide traffic information
    b. Use of traffic information to initiate radio contact and query ATC
    c. Display TCAS RAs to ATC radar displays
    d. Trigger anti-collision light on the UAS to improve the likelihood of manned aircraft visually acquiring the UAS

2.1.2 Selection Rationale

The core reasons for UAS community requests to use TCAS on UAS, have been to reference the display for situation awareness and to execute self separation maneuvers in a bid to comply, or partially comply, with 14 CFR 91.111 and 91.113 to see and avoid and to remain well clear of other aircraft.

Several factors emerged during the selection process, which illustrated the need for focused study and consideration of the use of TCAS on UAS. Concerns generally focused on one of six areas:

1. The lack of clarity, widely varying concepts of operation, and poorly defined intended functions suggested by the UAS community for TCAS on UAS operating in the NAS
2. The TCAS display is subject to large discrepancies between intruder locations as presented on the traffic display versus their true locations
3. The lack of information about specific state parameters such as intruder range, vertical rate, heading, speed (or closure rate) and time to CPA
4. Projection of the intruder's future states (e.g. locations, speeds, etc.) must be estimated by a pilot's sampling of traffic trends on the display over time, and prone to misinterpretation and human error
5. The lack of intruder intent information on the TCAS display can mislead the pilot into incorrect estimates of an intruder's future state
6. UAS performance and control link delay considerations have not been addressed. These unknown variables can have major impacts on appropriate and effective interpretation and maneuvering

Candidate methods selected for detailed evaluation were those considered to provide the most benefit with the highest potential for safely accomplishing their candidate function. Simple, one dimensional, maneuvers to remain well clear of a single intruder were considered more likely to pass the evaluation criteria than the more complex maneuvering solutions against multiple simultaneous intruders. Finally, candidate methods which perform the function of self separation were considered more likely to pass the evaluation criteria as they provide more time for the pilot to assess encounters and result in a less severe outcome than the collision avoidance methods. Therefore selection focused on the candidate function of self separation using methods with maneuvering solutions in one dimension only (e.g. vertical maneuver).

Table 2 details the rationale for excluding methods for analysis.

Table 2 Methods Deferred for Analysis

#	Candidate Function: Candidate Method:	Rationale
1a	Function: Collision Avoidance Method: Vertical maneuver to avoid intruders depicted as a TA on the TCAS traffic display	Collision Avoidance functions implemented through pilot interpretation of the traffic display are considered unachievable due to both limitations in the displayed traffic information (e.g. completeness and accuracy) and the pilot's inability to make effective and reliable maneuvering decisions on the traffic display alone given the short time (48-20 seconds) from the issuance of the TA to CPA. The Catastrophic severity consequences of an incorrect collision avoidance maneuver levy an unachievable probability requirement for acceptable risk where human performance is the predominant role in achieving the intended function. This conclusion was arrived at by subject matter expert opinion, negating the need to perform an exhaustive PHA on an operational concept in each class of airspace.
1b	Function: Collision Avoidance Method: Horizontal maneuver to avoid intruders depicted as a TA on the TCAS traffic display	
1c	Function: Collision Avoidance Method: Maneuver in response to a TCAS Resolution Advisory	Complying with the RA guidance necessitates an assessment of the system from requirements definition to a system safety assessment of the architecture (including the UAS pilot). The PHA is not the appropriate tool to perform an end to end safety assessment on a specific architecture or implementation. The safety assessment should address 1) lack of visual acquisition, 2) response to RAs (time and vertical acceleration), 3) the distributed nature of the system architecture over a data link - TCAS processor to display, and pilot interface with the UA, 4) dependencies with other systems on the aircraft that are certified to applicable 14 CFR airworthiness standards, and 5) other design aspects of the system that would be uncovered during

		the system safety assessment.
2c	Function: Self Separation Method: Provide self-separation through speed changes	Self-separation through the use of speed changes was considered the least effective method to provide the candidate function within the time available to achieve well clear when compared to vertical or horizontal maneuvers. The effect of speed changes are difficult to assess without intruder speeds or closure rates directly provided on the traffic display. Self-Separation through speed changes also share common causal factors and outcomes as horizontal and vertical maneuvering.
2d	Function: Self Separation Method: Maneuver to resolve multiple simultaneous threat aircraft	Identifying multiple simultaneous threats from multiple intruders on the display is more complex and difficult than identifying a single threat. This could reasonably be expected to represent the same or higher level of risk, than maneuvering against a single intruder.
2e	Function: Self Separation Method: Self-separate and sequence at uncontrolled airports	Self-separation and sequencing at uncontrolled airports is complicated by combinations of vertical and horizontal maneuvering simultaneous with speed changes in the traffic pattern making this a complex, simultaneous, multi-intruder self-separation problem. Aircraft are frequently operating in close proximity, often maneuvering, to establish proper sequencing for approach and landing. These scenarios would be expected to result in higher levels of risk as compared to aircraft maneuvering in Class E or Class G airspace. Non-transponding traffic, which TCAS would not track, are also prevalent at uncontrolled airports.
2f	Function: Self Separation Method: Perform delegated separation similar to visual separation procedures	Same hazard, causal factors and outcomes as vertical (2a) or horizontal (2b) maneuvering in various system states.
2g	Function: Self Separation	Same hazard, causal factors and outcomes as vertical (2a) or horizontal (2b)

	Method: Stay in a "dark area" of the display by maneuvering away from traffic shown in a particular quadrant of the display	maneuvering in various system states. Non-transponding traffic, which TCAS would not track or display, is present in various system states.
3b	Function: Situation Awareness Method: Use of traffic information to initiate radio contact and query ATC.	The use of the TCAS traffic display and the limitations associated with its surveillance data was determined to provide less capability than the more complete traffic information provided to the Air Traffic Control system (e.g. more complete state data representation and verification, integrity monitoring, aircraft identification, intruder intent and clearance limits). The pilot-controller exchange and associated VHF radio receive-transmit load was considered to increase Air Traffic Controller workload and function to provide the flight crew with information lacking from the traffic display (i.e. a gap filler), more often than providing for a specific pilot action or decision for maintaining or achieving safe separation distances or continued safety of flight.
3c	Function: Situation Awareness Method: Display TCAS RAs to the air traffic controller on a radar display.	The function of providing RA guidance to the air traffic controller was too vague to identify specific hazards resulting from its use. This is also considered to provide situation awareness to a third party (ATC) and not a candidate method specific to the UAS. Providing TCAS RA information to a controller is not considered substantively different than for manned aircraft and more applicable to the Air Traffic domain than aircraft systems engineering or operations.
3d	Function: Situation Awareness Method: Trigger anti-collision light on the UAS to improve the likelihood of manned aircraft visually acquiring the UAS	The method was not able to be decomposed to identify hazards associated with its use. This is also considered to provide situation awareness to a third party (other aircraft) and not a candidate method specific to the UAS.

Complying with the RA guidance necessitates an assessment of the system from requirements definition to a system safety assessment of the architecture (including the UAS pilot). The PHA is not the appropriate tool to perform an end to end safety assessment on a specific architecture or implementation.

To accomplish such an assessment there are a number of activities that would need to be completed. Section 5 outlines areas of future work that would need to be accomplished to support such an assessment. These include but are not limited to flight testing, modeling/simulation and/or analysis to validate accepted concepts and their underlying assumptions, distributed architecture, human factors, automation, autonomy, and UAS performance.

2.1.3 List of Methods Evaluated

The process of prioritizing candidate methods for analysis identified commonalities between many of the candidate methods. Therefore, the candidate methods that were evaluated using the PHA process were reduced to the following:

- Vertical maneuver to remain well clear from intruders depicted as proximate traffic or other traffic on the TCAS traffic display
- Horizontal maneuver to remain well clear from intruders depicted as proximate traffic or other traffic on the TCAS traffic display
- Use of TCAS traffic display to provide traffic information

2.2 Evaluation Process

A safety evaluation is essential to determine the feasibility, practicality, and potential impact on the NAS of each of the methods identified for the use of TCAS on UAS. To ensure a comprehensive and robust evaluation is preformed, the process selected by the workgroup was aligned with the FAA's Safety Risk Management (SRM) process. The evaluation process specific to this study is illustrated in Figure 1. The SRM process is a part of the overall Safety Management System (SMS)[13] in place at the FAA. It is a systematic and comprehensive analytical approach for managing safety risk at all levels. The SRM process is a means to:

1. Document proposed NAS changes regardless of their anticipated safety impact
2. Identify hazards associated with a proposed change
3. Assess and analyze the safety risk of identified hazards
4. Mitigate unacceptable safety risk and reduce the identified risks to the lowest possible level
5. Accept residual risks prior to change implementation
6. Implement the change and track hazards to resolution
7. Assess and monitor the effectiveness of the risk mitigation strategies throughout the lifecycle of the change

[13] ATO Safety Management System Manual

8. Reassess change based on the effectiveness of the mitigations

In an effort to standardize the process for performing a safety evaluation, the workgroup used the FAA Air Traffic Organization SMS Manual as guidance for PHAs as well as severity and likelihood definitions, and this formed the basis for a risk determination.

The results of the SRM process provide a viable means upon which decisions for acceptance of each method can be based. Before identifying and evaluating the hazards for risk, however, a clear understanding of the method and its concept of use is necessary. It is also important to understand the process and decision flow associated with a given function.

To that end, the process for evaluating the methods was created with the following steps.

1. Definition of the concept of use for each method
2. Evaluating the process and decision flow for each method
3. Development of a PHA
4. Decision criteria based on a risk matrix

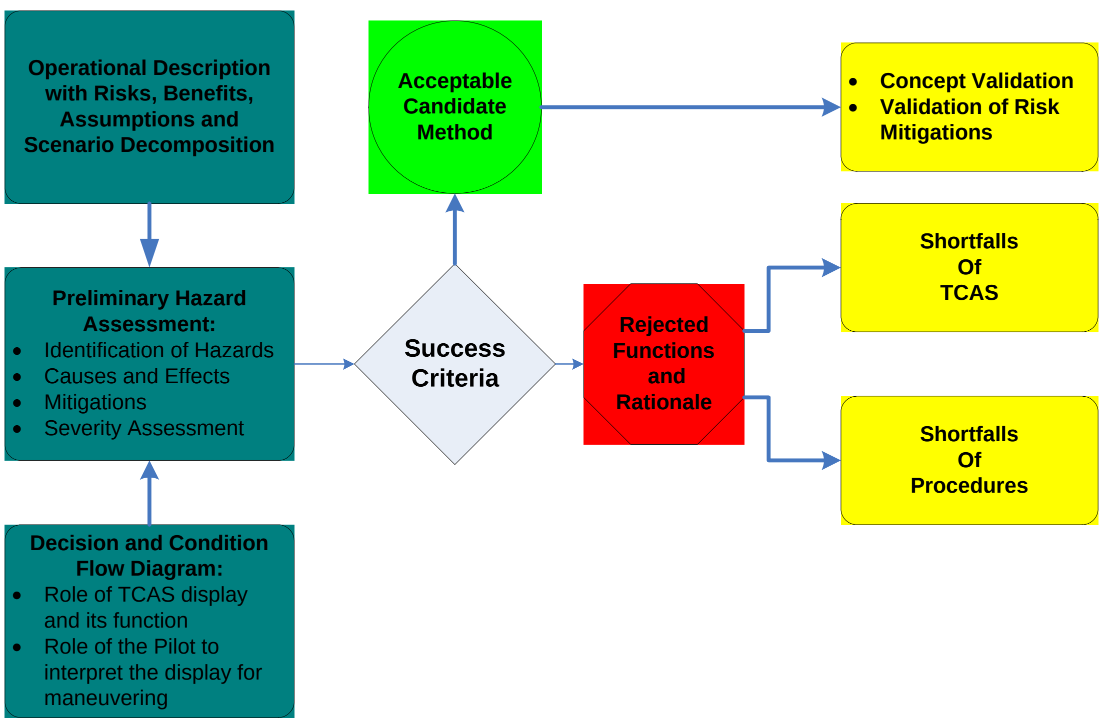

Figure 1 – Candidate Method Evaluation Process

2.3 Concept of Use

With the exception of situation awareness, the methods listed in section 2.1.1 represent potential ways a UAS pilot could use a TCAS display and act on the information it displays when operating in the vicinity of other traffic. In addition, each candidate method is considered in all applicable classes of airspace.

During flight, TCAS displays would be used to enhance situation awareness. Displays, which have a range selection capability, would be used in an appropriate range setting for the phase of flight. For example, use minimum range settings in the terminal and longer ranges for climb/descent and cruise as appropriate.

AC 120-55B[14] states: “Do not deviate from an assigned clearance based only on TA information”. AC 20-151A[15] states “Maneuvers based solely on a traffic advisory (TA) or on information displayed on the traffic display are not authorized.” Two (2) of the three (3) candidate methods use TCAS in ways that are contrary to this guidance and would allow for horizontal and vertical maneuvers based solely on traffic depicted on a TCAS traffic display. The third method would use the display solely to provide situation awareness. The Concepts of Use discussed in this section is specific to the horizontal and vertical maneuver. The Concept of Use for the SA method is described in section 2.3.

When evaluating an encounter on the TCAS display, the pilot must perform a state estimate and trajectory projection to judge the timeframe and likelihood for which a threat condition might occur. Specifically, the pilot continually categorizes each intruder for monitoring or action.

Each candidate method includes specific boundaries to distinguish between maneuvers for self-separation and maneuvers intended to provide collision avoidance. As applicable to TCAS, the boundary between self separation and collision avoidance could be interpreted to be the point where the TCAS RA is issued – i.e. the TCAS RA is a collision avoidance maneuver and any maneuver made prior to the issuance of the RA could be considered for the purpose of self separation. Any maneuvering on the TCAS TA would be considered a maneuver to maintain safe separation or “well clear” of the intruder, as the maneuver is prior to the issuance of an RA. The current design of the TCAS traffic display, however, does not provide any means to determine where the boundary between TA and RA is located in time or relative position (range and altitude).

All of the candidate methods evaluated require operating TCAS in the TA-only mode, so that no RAs would be issued. When operating in TA only mode, an encounter that would normally generate an RA in TA/RA mode would only generate TA symbology. Because it retains TA symbology, the change in threat level (progressing from TA to RA) would not be annunciated to the pilot. Therefore, for the purposes of these analyses, maneuvers against a TA (solid yellow circle) are conservatively considered collision avoidance

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[14] AC 120-55B 11.b.1

[15] AC 20-151A , Appendix A, section I, Limitations

maneuvers. Maneuvers against "other traffic" (empty diamond) and "proximate traffic" (solid diamond) are considered self separation maneuvers. This distinction does not strictly conform to the design principles of TCAS. See Appendix D for a more complete description of TCAS symbology.

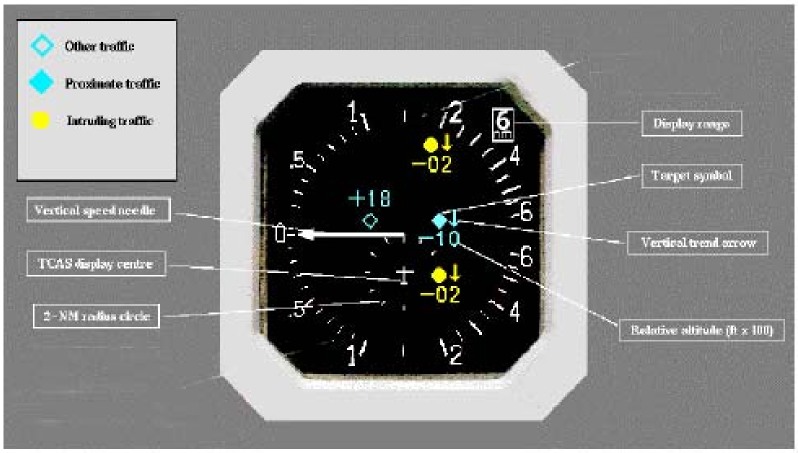

Figure 2 – Nominal TCAS Display (in TA only mode)

2.4 Information Flow and Decision Process

The pilot's selection of a maneuver, based on the interpretation of the TCAS display, could be derived either on the correct or incorrect placement and depiction of traffic information on the traffic display and either a correct or incorrect pilot interpretation of the traffic situation and state estimates.

The TCAS unit and traffic display could introduce a hazard by erroneous display of the data elements provided on the display. The most important of these data elements are:

- relative altitude
- vertical trend vector
- bearing
- range

Errors in display information and/or pilot interpretation of the display information could result in the pilot choosing an incorrect maneuver (vertical sense, vertical rate or heading change) to avoid an intruder that has been classified as a pilot determined threat. By observing the display during an encounter, the pilot will assess the threat posed by an intruder and determine what the pilot believes to be an effective and appropriate maneuver. This information would include closure rate, intruder trajectory and CPA; these attributes are not directly presented on the display but would have to be estimated. The pilot could also incorrectly estimate the state of his own aircraft (e.g. position, airspeed, altitude, etc.). Table 3 identifies the data elements required by the pilot to establish state estimates for the threat aircraft and ownship UAS, and the sources of those estimates (the TCAS display, UAS flight displays or other sources). These data elements and the effects of errors leading to an incorrect maneuver are identified as the causes leading to the hazard. The pilot would have to evaluate each of these elements for each intruder depicted on the TCAS traffic display.

Table 3 State Estimate Variables

Data Element	UAS	Intruder(s)
Position • **Azimuth** • **Altitude** • **Range**	FMS/Map	• Azimuth (Pilot Estimate) • Altitude (relative alt directly from TCAS traffic display) • Range (Pilot Estimate)
Vertical Trend	VSI (ADC)	Directly from TCAS display
Vertical Rate	VSI (ADC)	Pilot Estimate from TCAS Display
Direction (Heading)	HSI (INS/GPS)	Pilot Estimate from TCAS Display
Speed	ASI (ADC)	Pilot Estimate from TCAS Display
Intent	FMS/flight plan	Pilot Estimate
Intruder identification	**Not Applicable**	Pilot Estimate
Threat Level **Other Traffic** **Proximate Traffic** **Traffic Advisory** **Resolution Advisory**		Directly from TCAS display
Equipage	Pilot Knowledge	Pilot Estimate from location (airspace) or ATC
Aircraft Performance	Pilot Knowledge (from AFM)	Pilot Estimate from knowledge of threat type
Airspace (Class/Location)	Pilot Estimate (from FMS/Map)	Pilot Estimate from TCAS

Color Legend
Estimates derived (interpreted) from TCAS traffic display
Data directly from UAS equipment and displays (including TCAS traffic display)
Estimates from other sources

Data errors or errors in interpretation could be manifested in any of the processes depicted in the process flow, shown in Figure 3, ensuing in the exposure of the hazard resulting from an incorrect maneuver.

Note: TCAS has inherent inaccuracies in its ability to determine relative bearing of traffic displayed. Depending on the elevation of ownship UAS (UAS in a climb or descent at greater than 10° to +20°), the bearing error may be as high as +/- 15°RMS or 45° peak. This can lead a pilot to believe that the target he/she is viewing on their display is in one location when in fact it could be in a position 15° to 45° different from that displayed.[16]

[16] DO 185B, section 2.2.4.6.4.2

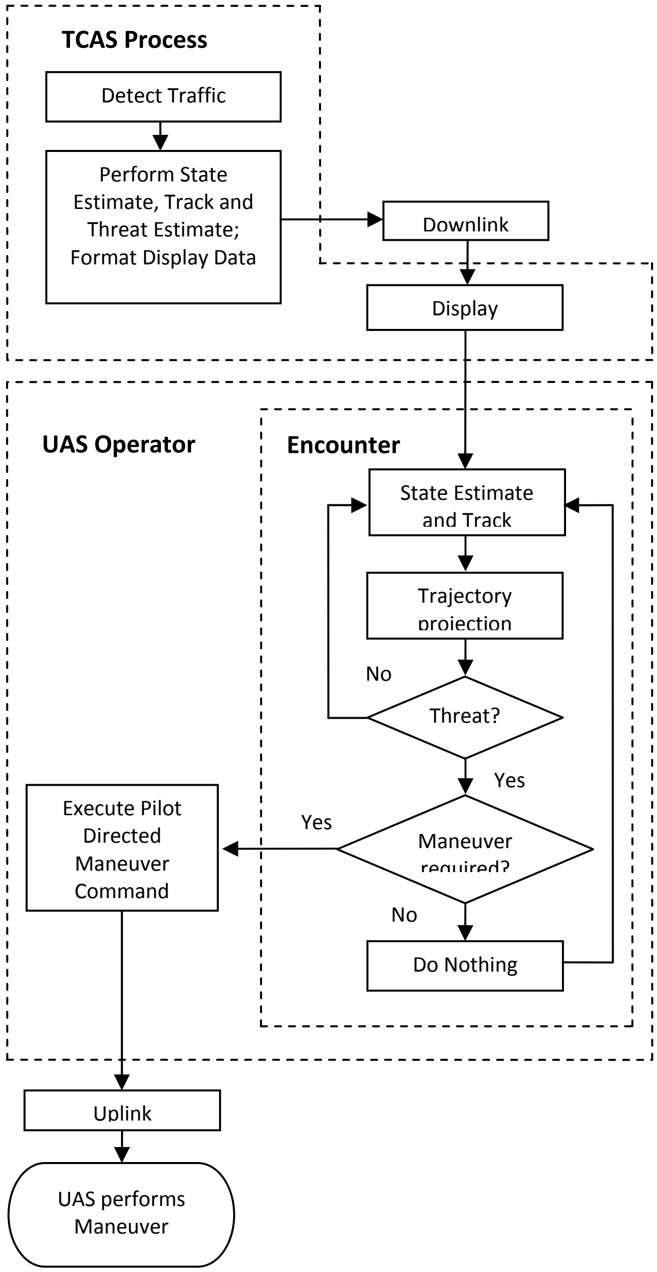

Figure 3 – TCAS Functional Block Diagram

The working group's approach to assessing specific risks resulting from the execution of a candidate method included the consideration of the existing controls (policy, equipage) associated with the operation of TCAS. Controls present in the different classes of airspace were also considered in the analysis (see system state in Figure 4). The working group then determined the worst credible potential outcome that could occur in the different system states. The particular effect (severity), and estimation of how often the particular effect is expected to occur (likelihood) was determined using a qualitative process based on the subject-matter expertise of the working group members. Quantitative data was considered where available to augment subject matter expertise. Although service history, simulation analysis and data were not directly applicable to establish quantitative probabilities, these quantitative data[17] were used to support qualitative likelihood estimates and established a basis for reasonableness on those estimates. The level of risk was determined based on the Severity and Likelihood determination. For medium and high risk determinations, the working group sought to develop additional mitigations (proposed controls) in an attempt to lower the initial risk to acceptable (Low-Medium in accordance with FAA policy).

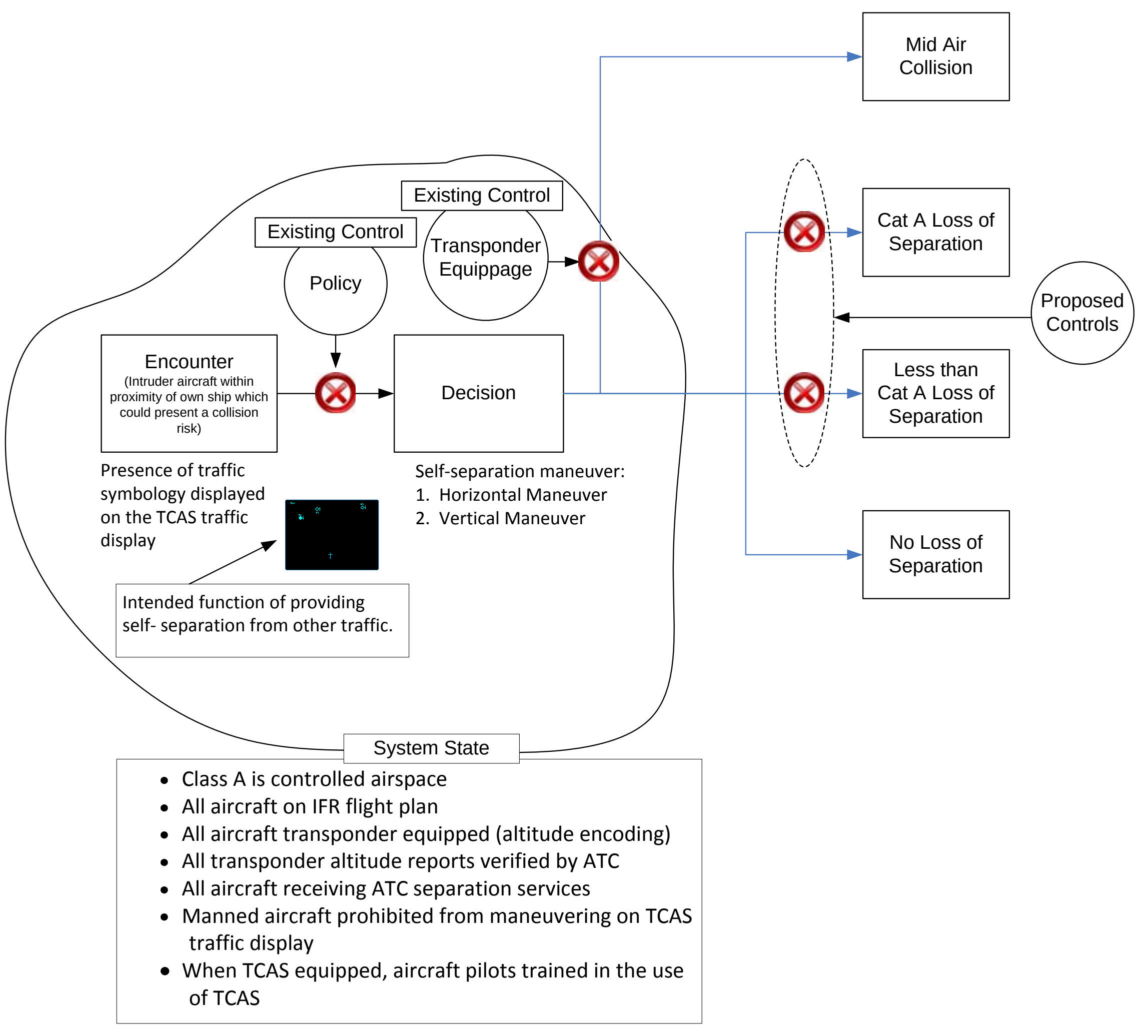

Figure 4 – Application of Controls to effect Risk Reduction (Class A Airspace shown)

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[17] MIT LL TOPA Overview, 2008 NALL Report

The causal events leading to the hazard resulting from an incorrect maneuver are depicted in the bow-tie model in Figure 5.

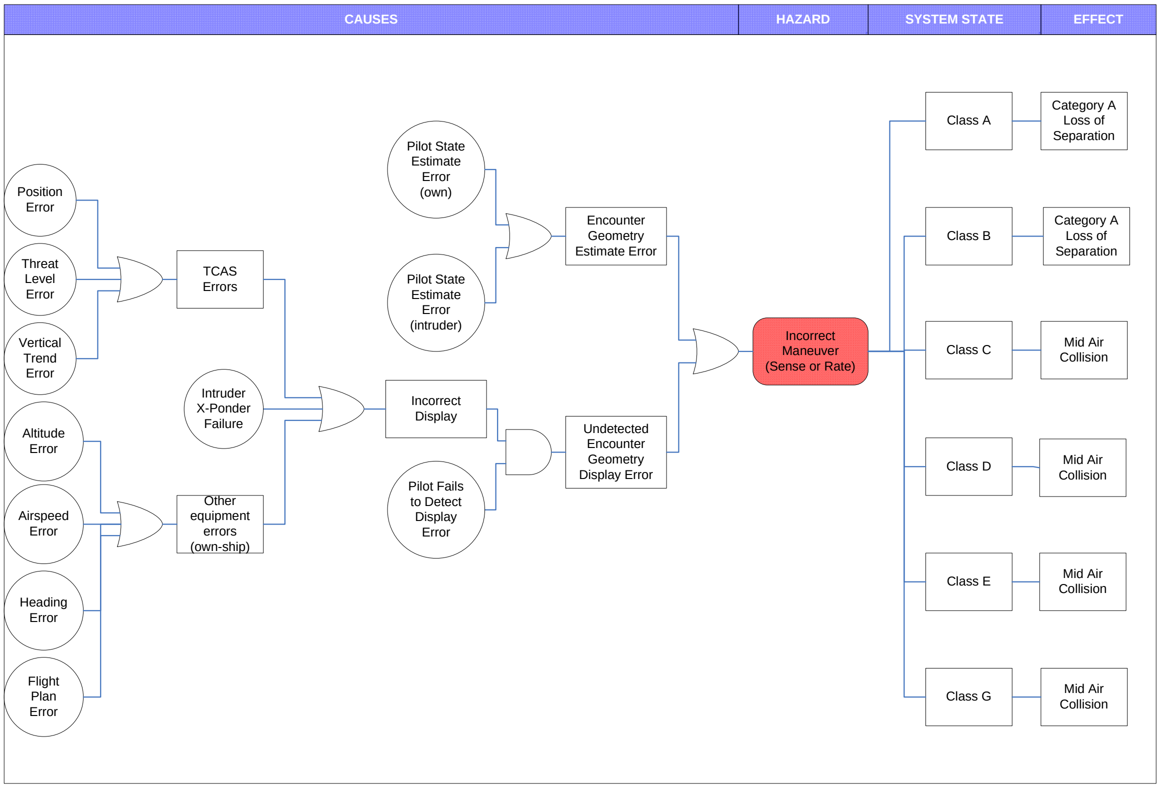

Figure 5 – Bow-Tie model of Incorrect Maneuver Hazard

The Bow-Tie model is a structured approach in which causes of hazards are directly linked to possible outcomes or effects in a single diagram. It is a combination of fault tree and event tree, and is a recognized means to conceptualize safety risk associated with hazards under various conditions.

In the bow-tie model, the root causes are listed at the extreme left of Figure 5. These root causes are reconstructed (moving to the right) until there are only two primary causes for the hazard; encounter geometry estimation error, and undetected encounter geometry error. The hazard, an incorrect maneuver (sense or rate), is then identified to be in one of the six system states; with in Class A, B, C, D, E, or G airspace. The effects of the hazard in a particular system state, are then listed; category A loss of separation (see Table 4) for Class A and B airspace, and mid-air collision for Class C, D, E, and G airspace.

For example, (going from left to right in the bow-tie model) a position error input into the TCAS system, could cause a TCAS error. This error could then lead to an incorrect display of traffic information. The incorrect display could cause an undetected encounter geometry error which could lead to a pilot making an incorrect maneuver. If this incorrect maneuver takes place in Class D airspace, the worst credible effect would be a mid-air collision.

2.5 Hazard Assessment

There are many processes and methods for conducting safety assessments. The method chosen for the evaluation of TCAS on UAS is the PHA (Table 4) using the FAA SMS as a guide. In this case, the objective was to consider the hazards introduced by using the existing design of the TCAS traffic display to support several potential functions beyond its originally certificated intended function. This process began with a description capturing its concept of use in the environment within which the system is envisioned to operate. These environments were partitioned into the classes of airspace in which the UAS would be operating as environmental considerations in the system state. Each class of airspace includes operating requirements and services which provide hazard controls. These controls may influence the individual outcomes resulting from the exposure of the hazard. Potential hazards exposed by these new concepts were identified, and then those hazards were evaluated against its operational use, functionality, TCAS hardware/software design assurance levels, procedures/processes, and human operators. There was then an analysis of the worst credible outcome in terms of severity (Table 5) affecting people, the environment, and equipment; as well as assessment of the likelihood (Table 5) of occurrence. This was followed by identification of risk mitigation measures as they pertain to system design, safety devices, procedures/training, and assurance.

This process of hazard analysis, in combination with the decision criteria, determines if a candidate methodology is considered to perform its function to an acceptable level of safety. It is envisioned that the candidate methods passing the decision criteria would undergo a more formal FAA SMS evaluation in addition to validation of proposed mitigation strategies and associated assumptions.

The SMS manual provides guidance on use of qualitative and quantitative data in assessing risk[18]:

1. Quantitative data is preferred as it tends to be more objective
2. Recognizes quantitative data is not always available
3. Accepts use of qualitative data and expert judgment of a team in the absence of quantitative data

Using qualitative data and expert judgment, these analyses focused on a hazard assessment of an individual UAS using one of these methods. This analysis adopts the second column of the Likelihood Matrix as the measure of likelihood of occurrence (Table 6; column titled “NAS Systems”; subtitle “Qualitative”; subtitle “Individual Item/System”).

[18] ATO Safety Management System Manual section 3.9.5

The evaluation did not consider NAS-wide deployment of UAS performing these methods concurrently.

Table 4 – Preliminary Hazard Analysis Tool

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement
	Any condition, real or potential; that results in injury, damage, etc. Prerequisite to an accident or incident	Events that lead to or results in a hazard or hazardous condition	Conditions present during performance of operation - Worst credible	Rules, equipment, procedures, training, etc., that are already in place for the purpose of reducing the potential for a particular effect to occur

Table 4 – Preliminary Hazard Analysis Tool (Continued)

(6) Possible Effect	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
Worst credible – potential outcome of a hazard for the system state	Particular effect of the identified hazard producing the worst credible outcome (likelihood is not considered)	Expression of how often a particular effect is expected to occur	Severity and likelihood of a hazard when it is first identified and assessed	Proposed controls to mitigate risk of a hazard's effects	Risk status predicted to occur when recommended controls or requirements are verified

Table 5 – Severity Classification

Effect On: ↓	Hazard Severity Classification				
	Minimal 5	**Minor** 4	**Major** 3	**Hazardous** 2	**Catastrophic** 1
ATC Services	Conditions resulting in a minimal reduction in ATC services, or a loss of separation resulting in a Category D Runway Incursion (RI)[1], Operational Deviation (OD)[2], or Proximity Event (PE)	Conditions resulting in a slight reduction in ATC services, or a loss of separation resulting in a Category C RI[1] or Operational Error (OE)[2]	Conditions resulting in a partial loss of ATC services, or a loss of separation resulting in a Category B RI[1] or OE[2]	Conditions resulting in a total loss of ATC services, (ATC Zero) or a loss of separation resulting in a Category A RI[1] or OE[2]	Conditions resulting in a collision between aircraft, obstacles or terrain
Flight Crew	– Flightcrew receives TCAS Traffic Advisory (TA) informing of nearby traffic, or, – PD where loss of airborne separation falls within the same parameters of a Category D OE [2] or PE – Minimal effect on operation of aircraft	– Potential for Pilot Deviation (PD) due to TCAS Preventive Resolution Advisory (PRA) advising crew not to deviate from present vertical profile or, – PD where loss of airborne separation falls within the same parameters of Category C (OE) [2] *or* – Reduction of functional capability of aircraft but does not impact overall safety (e.g., normal procedures as per AFM)	– PD due to response to TCAS Corrective Resolution Advisory (CRA) issued advising crew to take vertical action to avoid developing conflict with traffic or, – PD where loss of airborne separation falls within the same parameters of a Category B OE [2] or, – Reduction in safety margin or functional capability of the aircraft, requiring crew to follow abnormal procedures as per AFM	– Near mid-air collision (NMAC) results due to proximity of less than 500 feet from another aircraft or a report is filed by pilot or flight crew member that a collision hazard existed between two or more aircraft – Reduction in safety margin and functional capability of the aircraft requiring crew to follow emergency procedures as per AFM	– Conditions resulting in a mid-air collision (MAC) or impact with obstacle or terrain resulting in hull loss, multiple fatalities, or fatal injury

Table 6 – Likelihood Matrix

	NAS Systems & ATC Operational	NAS Systems		ATC Operational		Flight Procedures
		Qualitative				
	Quantitative	Individual Item/System	ATC Service/ NAS Level System	Per Facility	NAS-wide	
Frequent A	Probability of occurrence per operation/operational hour is equal to or greater than $1x10^{-3}$	Expected to occur about once every 3 months for an item	Continuously experienced in the system	Expected to occur more than once per week	Expected to occur more than every 1-2 days	Probability of occurrence per operation/operational hour is equal to or greater than $1x10^{-5}$
Probable B	Probability of occurrence per operation/operational hour is less than $1x10^{-3}$, but equal to or greater than $1x10^{-5}$	Expected to occur about once per year for an item	Expected to occur frequently in the system	Expected to occur about once every month	Expected to occur about several times per month	
Remote C	Probability of occurrence per operation/operational hour is less than or equal to $1x10^{-5}$ but equal to or greater than $1x10^{-7}$	Expected to occur several times in the life cycle of an item	Expected to occur numerous times in system life cycle	Expected to occur about once every year	Expected to occur about once every few months	Probability of occurrence per operation/operational hour is less than or equal to $1x10^{-5}$ but equal to or greater than $1x10^{-7}$
Extremely Remote D	Probability of occurrence per operation/operational hour is less than or equal to $1x10^{-7}$ but equal to or greater than $1x10^{-9}$	Unlikely to occur, but possible in an item's life cycle	Expected to occur several times in the system life cycle	Expected to occur about once every 10-100 years	Expected to occur about once every 3 years	Probability of occurrence per operation/operational hour is less than or equal to $1x10^{-7}$ but equal to or greater than $1x10^{-9}$
Extremely Improbable E	Probability of occurrence per operation/operational hour is less than $1x10^{-9}$	So unlikely that it can be assumed that it will not occur in an item's life cycle	Unlikely to occur, but possible in system life cycle	Expected to occur less than once every 100 years	Expected to occur less than once every 30 years	Probability of occurrence per operation/operational hour is less than $1x10^{-9}$

Central to the determination of Risk in the PHA process is the establishment of likelihood of the worst credible consequence resulting from hazard exposure. Methods which culminate in maneuvering the UA to avoid potentially conflicting traffic generally follow a process of the pilot evaluating traffic presented on the TCAS display, determining whether the traffic presents a threat to his aircraft's trajectory and determining any avoidance maneuvers to remain well clear or avoid collisions with aircraft presented on the display. This sequence and their generally evaluated likelihood estimates are presented in Figure 6, below.

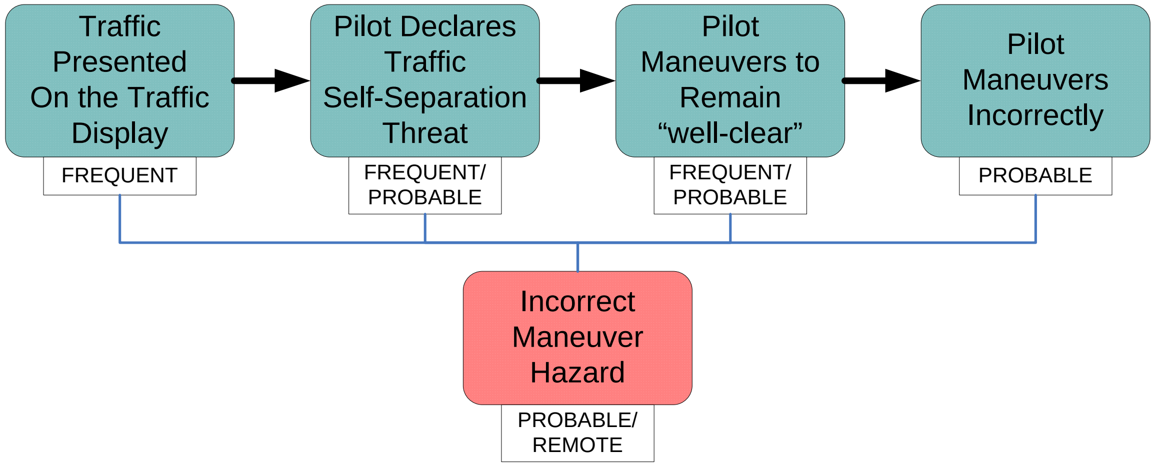

Figure 6 – Contributions to Likelihood

The likelihood of traffic being presented on the display is expected to be FREQUENT. Assuming a non-segregated operational environment for UAS, flying routinely in the NAS, UAS should expect to encounter aircraft depicted on the TCAS traffic display fairly frequently and could reasonably expected to have an traffic represented as other traffic or proximate traffic at least a few times on any routine flight.

The likelihood of pilots determining that an of the aircraft presented on the display would be determined as being on potentially converging flight trajectories requiring an adjustment in the UAS flight path is expected to be FREQUENT / PROBABLE. The probability will depend on the system state / airspace.

The likelihood of the pilot maneuvering, based on traffic information presented on the display (if so authorized under an operational approval) is expected to be FREQUENT / PROBABLE. Pilots could be expected to make adjustments to the UA flight path while routine operations in the NAS. The probability will depend on the system state / airspace. Although there was no applicable operational data to directly correlate the likelihood of performing an avoidance maneuver, the data reviewed[19] suggest that pilots maneuver FREQUENTLY when evaluated against the SMS criteria.

The likelihood of the pilot maneuvering incorrectly, based on traffic information presented on the display is expected to be PROBABLE. Pilots could be expected to make inappropriate adjustments to the UA flight while flying routine operations in the NAS where approach geometries, closing speeds, measurement bearing errors, and display inaccuracies lead to a pilot's inability to establish intruder state estimates with enough fidelity to determine an effective maneuver. Although there was no applicable operational data to directly correlate the likelihood of performing an incorrect avoidance

[19] Impact of Traffic Symbol Directional Cues… Kaliardos, IEEE paper

maneuver, data reviewed several sources[20,21,22] suggest that pilot's propensity to perform incorrect avoidance maneuvers is PROBABLE when evaluated against the SMS criteria.

2.6 Decision Criteria

The establishment of accept and reject criteria is important for evaluation of the candidate methods. These criteria set a foundation for recommending candidate methods for further development and evaluation through the SRM process, including validation of operational procedures and risk mitigation strategies. The analysis documented in this report is an initial evaluation to determine potential uses of TCAS which may be employed on UAS without introducing unacceptable safety risks into the NAS. Although a high level evaluation of benefits is included within the scope of this effort, those are not considered in the recommendation(s) for further evaluation. The decision criteria to accept or reject a candidate method are based on the safety of its application and the ability of operational mitigations to control hazards.

From Figure 7, any methods of using TCAS on a UAS with a risk higher than medium, or that cannot reasonably be expected to be mitigated to medium risk by rational operational mitigations, shall be rejected.

[20] EUROCONTROL ACAS II Bulletin No 6

[21] Impact of Traffic Symbol Directional Cues… Kaliardos, IEEE paper

[22] DO-298, SA-01 events

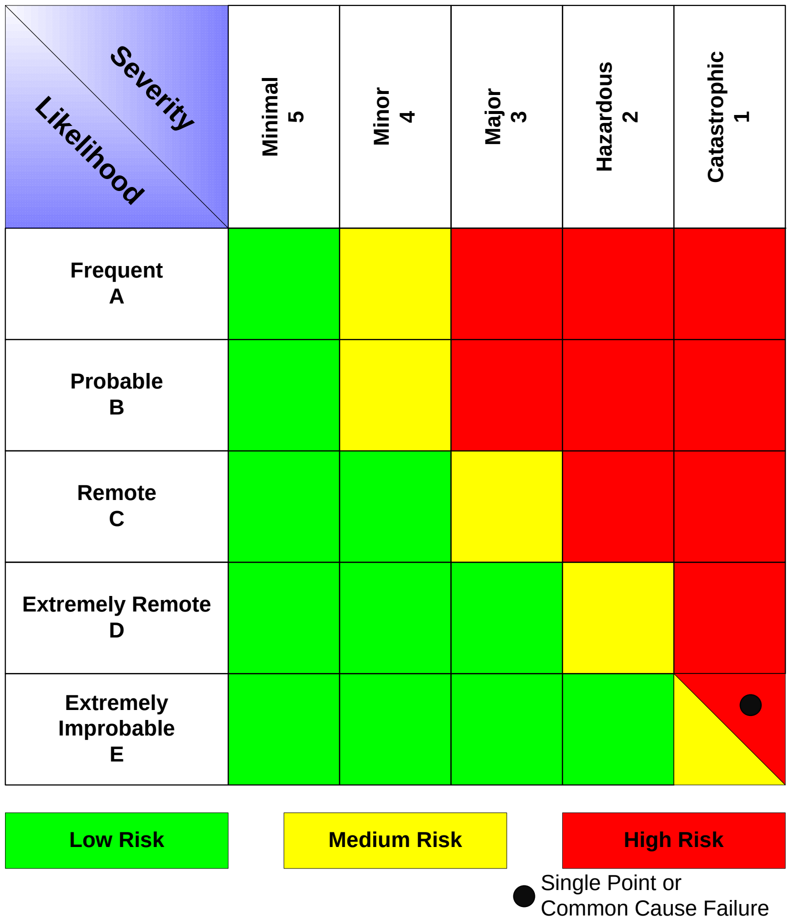

Figure 7 – Hazard Risk Matrix

Mitigation strategies and safety requirements are employed in hazard analysis to reduce the severity or likelihood of the worst credible outcome of an exposed hazard. The most effective method to mitigate and control hazards is to design risks out of the system in the definition of requirements and system design, followed by the incorporation of safety devices where changes to an existing design are impractical. Although these are considered the most effective strategies to control hazards, changes to the TCAS system or the incorporation of additional safety devices (e.g. independent means to validate position estimates) are out of scope for these analyses. Therefore, the only remaining strategies to control risks introduced by the use of the TCAS display, as evaluated in these analyses, are through the use of procedural mitigations and/or training. Procedural hazard mitigations are the least desirable methods to mitigate hazards; they are generally considered the least effective, the least reliable and the most difficult to measure/validate. Procedural mitigations and training are so difficult to effectively implement and validate that they are highly discouraged, or even prohibited by some System Safety standards, as the only strategy to mitigate Catastrophic, Hazardous (or Critical) hazards. Therefore, for the purpose of these analyses, procedural mitigations or training are not employed or proposed as risk reduction strategies to mitigate initial risk in these analyses to control Catastrophic or Hazardous hazards.

Where operational procedures and/or training are used as risk reduction strategies for severity consequences lower than Hazardous in the analyses, procedures must be reasonably expected and assumed to be performed reliably with consistent results and training should be reasonably expected and assumed to be effective in eliminating variability in human response and decision making.

Although it is conceivable for a mitigation to limit the likelihood of exposure through applying a control or multiple controls substantiated by service history or operational data, it is difficult to apply a control or multiple controls to reduce the severity of a hazard by more than one severity consequence in a qualitative analysis. Therefore, for the purpose of these analyses, mitigations are only used to reduce the severity of the consequences of hazard exposure by one severity category (e.g. from catastrophic to hazardous) regardless of how many layers of mitigations are considered. In any follow-on evaluations it may be acceptable for an applicant to propose mitigations that may lower the severity by two levels; however they must be validated with applicable service history or substantiating data to be measurable, repeatable and objective.

3 Function hazard assessments

The TCAS system may have multiple intruders displayed at any given time, requiring the pilot to evaluate the threat level of each intruder presented on the display. The pilot may decide that maneuvering might be required to maintain well clear of some aircraft, while others may simply require monitoring. Most encounters which induce the pilot to take maneuvering action are likely to be pair-wise threats where the pilot maneuvers to maintain well clear from the threat. The maneuvering decision may take into account the relative positions and perceived motion of other displayed aircraft in the decision process, but multiple, simultaneous threats are expected to be rare compared to pair-wise threats. When multiple, simultaneous threat encounters do occur, the geometry will likely be too complex for the pilot to definitively determine an effective single maneuvering solution to avoid all threats. Therefore, even when presented with multiple intruders on the TCAS traffic display, the analysis focused on maneuvering solutions against pair-wise threats.

3.1 Horizontal maneuver to remain well clear of a single threat/intruder

In 1995, research on TCAS III sought to enhance the capabilities of TCAS II by providing additional threat resolution in the horizontal plane. This research solely addressed using TCAS for collision avoidance.[23]

It was found that TCAS III's ability to resolve encounters in the horizontal plane was limited by the accuracy of the horizontal miss distance estimation, and the miss distance estimate is directly related to the degree of the intruder's bearing rate error. The bearing measurements can contain relatively large errors due to limitations in the TCAS III antenna subsystem. Note that the TCAS III antenna subsystem had enhanced bearing accuracy as compared to TCAS II.

The bearing measurement errors caused by electromagnetic scattering of the airframe and nearby objects, result in large errors in the intruder bearing rate error, and consequently large miss distance estimation errors. The analysis results show that it was nearly impossible to monitor the separation progress using miss distance estimates derived from bearing rate estimates.

The uncertainties in the estimated miss distance of the intruder throughout the encounter, coupled with the inherent lag in the bearing tracker, made the TCAS III horizontal RAs maneuver too inaccurate to adequately support collision avoidance. Consequently, the TCAS III program was cancelled.

[23] ATC-231 TCAS III Bearing Error Evolution

The same errors are believed likely to impair the self separation candidate method using a horizontal maneuver based on data displayed by a TCAS II system.

3.1.1 Functional Description

The TCAS Horizontal Maneuver – Self Separation function uses the relative position, altitude and vertical trend indication (climbing/descending arrow) on the traffic display to provide sufficient information for the pilot to alter course around another aircraft's position while maintaining a safe distance away from it. By utilizing the TCAS traffic display, a horizontal strategy is established based on a fixed distance from the intruder to ownship UAS.

A UAS pilot needs to consider the following when making a decision:

1. Knowledge of intruders historical trend as displayed
2. Bearing indicated on the display may have large errors (peak error ±27º).
3. Estimated time to CPA
4. Estimated lateral separation and vertical separation at CPA
5. UAS performance limitations (e.g. turning performance) at present altitude
6. Potential intent of intruder (e.g. ATC clearance and instructions)
7. Airspace in which UAS is operating (e.g. potential closing speeds)
8. Traffic that may not be displayed on TCAS display (not transponder equipped)

3.1.2 Assumptions used in this analysis

1. TCAS is operated in TA only mode
2. If a TA is received, the UAS pilot will not maneuver
3. If the UAS pilot is instructed by ATC not to maneuver, the UAS pilot will comply
4. No other displayed traffic information is available to the pilot (e.g., radar display, Automatic dependent surveillance-broadcast (ADS-B) display)
5. Information latency will not degrade safety of maneuver
6. TCAS will be operated in a continuous traffic display mode
7. The UAS pilot will only use horizontal maneuvers to maintain well clear upon declaration of a pilot determined threat
8. Specialized TCAS maneuver training including vehicle specific performance limitations is required
9. UAS are authorized to maneuver using the TCAS display

3.1.3 Scenario Description

To illustrate the exposed hazard, this paper develops a nominal scenario. The intent of presenting a scenario is not to represent all conditions under which the hazard is exposed, but to generally outline example conditions under which operations would be expected within the NAS. The scenario is exemplary of the "system state" where the worst credible hazard might be exposed. Many other scenarios would be possible within each system state. See the PHA tables developed in Appendix F for a complete assessment of all airspaces.

Ownship UAS is traveling from south to north (Heading HDG-360), in level cruising flight (Flight Level FL310). The UAS is on an Instrument Flight Rules (IFR) Flight Plan.

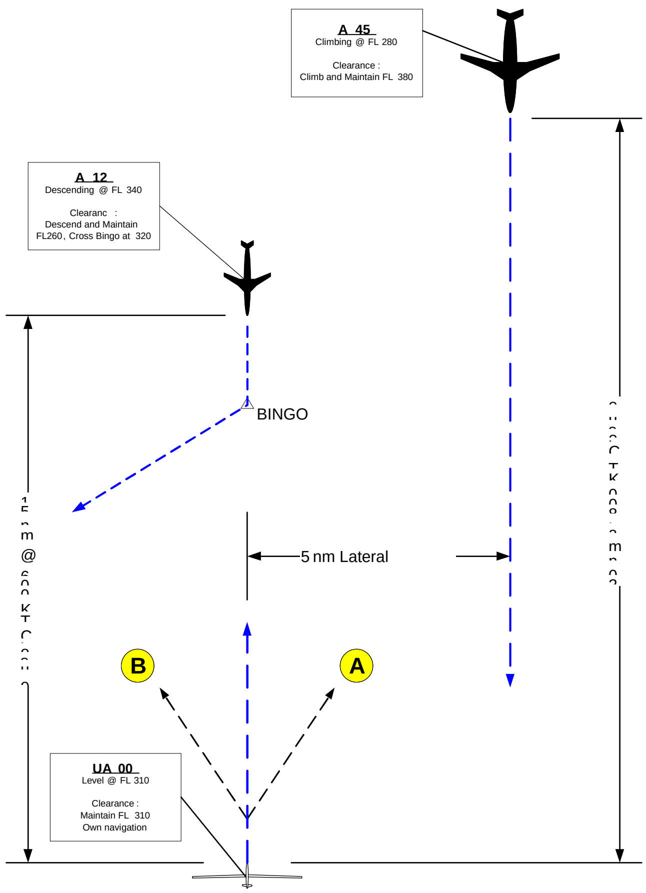

Figure 8 – Plan view – Horizontal Maneuver for Self-Separation

Conflicting traffic is traveling south (HDG-180), descending toward our altitude from FL340 to FL320 before turning. The intruder is flying under an IFR flight plan.

A second aircraft is not yet on the TCAS display. When it becomes visible, it could influence the pilot's initial maneuver; it could induce additional maneuvering.

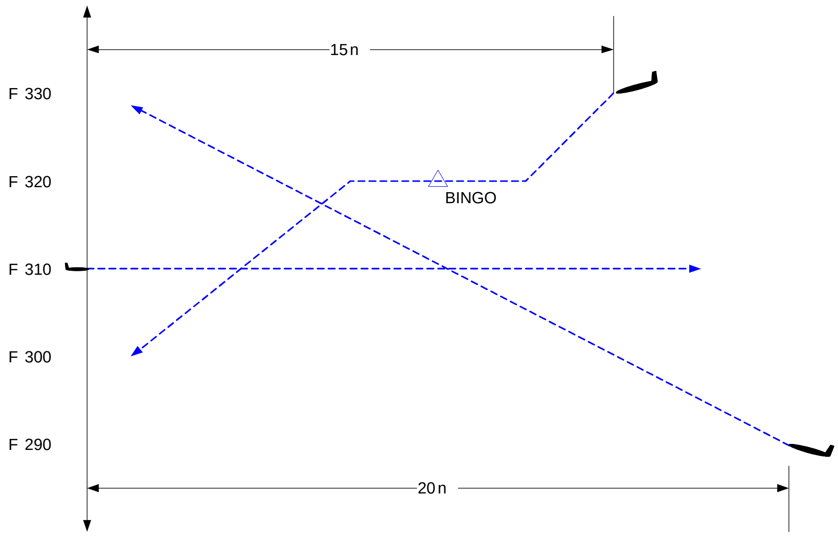

Figure 9 – Profile view – Horizontal Maneuver for Self-Separation

On the TCAS traffic display, the initial conflicting traffic is displayed as other traffic (empty diamond). The pilot may adjust the TCAS display range from 40 NM to 20 NM as needed.

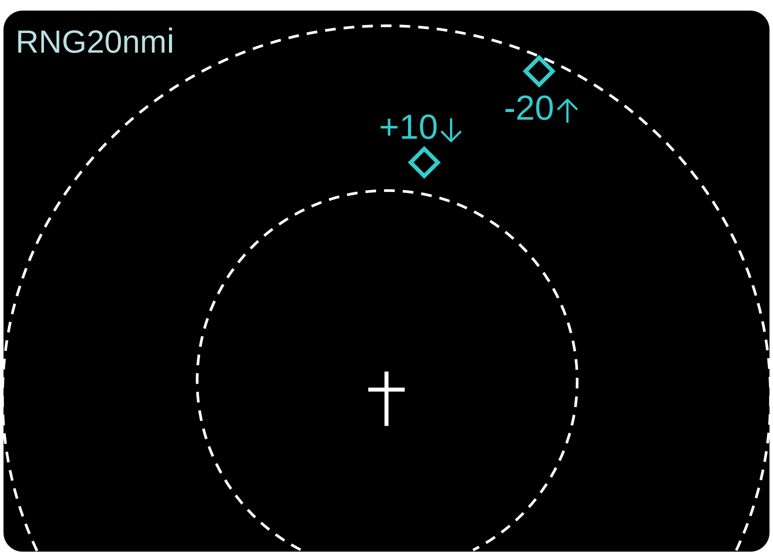

Figure 10 – TCAS Display for Horizontal Maneuver

The UAS pilot is monitoring the TCAS display and observes the one traffic icon displayed at twelve o'clock and a second, new, traffic icon at one o'clock. The pilot has been tracking the traffic since it entered the vicinity, and has observed it closing. When the pilot first observed the traffic, it was 3000 ft above ownship UAS. When the traffic at the twelve o'clock position is within 20 NM of the UAS, the pilot reacts. The traffic appears to be descending through the UA's altitude – the altitude separation is approaching 1000 ft and appears to be closing.

The UAS pilot makes a 30 degree left turn; his intent is to allow the intruder to pass ahead of ownship UAS to the right; the UAS will return to course when well clear.

1. Detect traffic. The UAS pilot incorporates TCAS display into instrument scan on a frequent revisit rate. During one scan, the pilot sees that traffic is displayed on TCAS and begins to monitor the intruder traffic.
2. State estimation and tracking. The UAS pilot is now continuously monitoring the intruder traffic to begin to develop a trajectory projection. During this tracking, the UAS pilot will change the TCAS display range to gain resolution to determine the distance to the intruder and to answer the following questions.
    a. Does the intruder appear to be closing with the UAS in range, or is it pulling away?
    b. What is the vertical rate of change of the intruder, if any? (If less than 500 feet per minute (FPM), there will be no trend arrow displayed.)
    c. Does the intruder bearing appear to be on an intersecting geometry?

In this example scenario the pilot has determined that the intruder aircraft is closing in range and descending, feeding into the trajectory projection.

3. Trajectory projection. Based on the steps above, over time, the UAS pilot has converted his iterative state estimation to a trajectory projection. Although bearing accuracy of the TCAS system has known inherent errors, the primary information that the UAS pilot will use in his trajectory projection is range, range rate and bearing angle. The secondary information that the UAS pilot will use in his trajectory projection is relative altitude and vertical rate. Note that range, range rate, and vertical rate of change are estimated from the interpretation of the display and not directly available as numeric values from the display.

In this example scenario the pilot has estimated that the intruder aircraft will pass within 1000 ft vertically and less than 6 miles horizontally.

4. Threat declaration. If the projection of the intruder aircraft will not intersect the UA's flight path (range and altitude) then the UAS pilot will consider the intruder not to be a threat. This will be an iterative process as the resolution of traffic and ability to detect relative motion at the 40 NM maximum display range of TCAS is less than it will be at a closer (e.g. 20 NM) display range. Different pilots will declare a threat at different points throughout an encounter. One pilot may use a threshold based on estimated time-to-CPA, while another may use a threshold based on estimated distance-to-CPA. Also, pilots may make different assumptions regarding an intruding aircraft's speed (the pilot may be able to estimate relative closing speed from the display, or he may simply assume the intruder is flying at

maximum speed allowed in the airspace). The pilot's training and experience also influences when the pilot will declare the encounter a threat. The pilot must initiate the maneuver at such a time that a TA is not issued by the ownship UAS TCAS (i.e. assured to remain well clear).

In this example scenario, the pilot estimates that the traffic is approximately 20 NM away and closing and estimates their trajectories will be within 1000 ft vertically, and declares a threat that requires a maneuver. The pilot calculates a notional distance as determined from a worst case relative closing speed of 800 knots (for near head-on geometry, 20 NM corresponds to about 90 seconds to CPA).

5. Resolve. Upon determination that a threat exists, the UAS pilot will attempt to resolve the threat. The options to resolve the threat are:
    a. Do nothing-no maneuver necessary or allowed (if closer than the predetermined minimum maneuvering range or if instructed by ATC not to maneuver.
    b. Alter heading. If the UAS pilot calculates that a maneuver is warranted, he will initiate a left or right turn depending on the result of his trajectory projection in item 3 above. The UAS pilot will turn at a rate that will not initiate or trigger a TA on ownship UAS TCAS, and will initiate the minimum deviation to provide for self separation.

In this example scenario, the UAS pilot will turn left 30 degrees to pass to the left of intruder traffic and return to course once achieving horizontal separation to be well clear.

6. Execute turn. The UAS pilot will send a command to the UAS to execute a turn (change course), and will inform ATC that they are "UAS Global View 123, initiating a left turn on TCAS displayed traffic".

Upon completion of the successful separation maneuver and subsequent passing of the target traffic, the UAS pilot will inform ATC that they are clear of traffic and returning to their original course unless otherwise directed by ATC.

3.1.4 Development of a Preliminary Hazard Analysis

Any maneuver for the purpose of maintaining self separation may result in the effect of "loss of separation" and potentially result in the need to perform a collision avoidance maneuver to avoid a mid-air collision. The complete PHA analysis can be found in Appendix F.

The hazard is exposed when the pilot makes an incorrect self-separation maneuver by:

- Initiating a left turn maneuver
    - Change of heading
- Initiating a right turn maneuver

    - Change of heading
- Roll to level from a previous turn
- Remaining on a heading when a change of heading was required

The causes of the hazard stem from pilot state estimation and interpretation errors as well as from equipment and display errors.

The first cause comes from errors in the pilot's ownship UAS state estimation. Since all of the state variables are directly readable from the pilot's Primary Flight Display (PFD), the principal cause for concern is latency of displayed information, pilot workload issues or distractions, and possibly differences in the pilot's perspective (the pilot being on the ground and not experiencing real flight).

The second cause comes from errors in the pilot's estimation of the intruder's state variables. From Table 3 (State Estimate Variables), the pilot must monitor the TCAS display for several seconds to track the intruder's azimuth and range, and must estimate a rough trajectory projection. Given the trajectory appears to be an intersecting geometry; he must estimate how long it will take to reach CPA with the intruding aircraft. With this time-to-CPA estimate, the pilot must further project the intruder's likely change in altitude based on currently displayed altitude and vertical trend indicator. He must also project his ownship UAS altitude based on his flight instruments. Finally, the pilot must speculate as to the other pilot's intent (the intruder might change course according to his flight plan or traffic pattern; he might see and avoid).

The third cause comes from possible equipment errors and algorithm limitations. TCAS errors generally stem from system limitations, and include imprecise azimuth resolution (position), reduced tracking accuracy and symbol placement during a maneuver, and limited display resolution for the intruder's vertical trend. Other intruder errors could cause ownship UAS TCAS to misrepresent the relative altitude (e.g. a data fault or altimeter fault). UAS equipment errors could also generate misrepresentations in the PFD for altitude, airspeed, heading, or flight path. Latency of the displayed data also introduces errors because the actual position of the intruder has already changed. Some equipment errors can be detected by the pilot or ATC, providing effective procedural control for these errors.

A fourth cause comes from uncooperative intruders (e.g. an intruder with no transponder or failed transponder) which may be missing from the display.

The system state is predominantly expressed by class of airspace. The sections which follow assess the worst credible outcome for each class.

3.1.5 Results/Observations

Performing a horizontal maneuver using the TCAS traffic display is not acceptable in Class A, B, C, D, E and G airspace, based on the PHA which indicates the risk is high and fails the acceptance criteria. The traffic display may introduce substantial errors in estimating intruder state (e.g. position, velocity), projections of intruder future state and collision risk could be introduced by limitations in the TCAS traffic display and associated data. This could result in an incorrect horizontal maneuver resulting in a loss of separation, require a collision avoidance maneuver, or result in a mid-air collision. Additionally, sufficient operational mitigations have not been identified which would reduce the risk of the TCAS horizontal maneuver in any airspace to an acceptable level.

From ACAS Bulletin[24]:

> The TCAS traffic display is designed to assist the visual acquisition of surrounding aircraft. There is a risk that some aircraft in the vicinity might not be displayed and in addition, due to bearing inaccuracy, a moving reference, and a lack of a speed vector, together with no identity information, flight crews could wrongly attribute a target symbol on the TCAS traffic display. Air traffic controllers base their actions on the comprehensive information shown on the radar display, which enables them to provide a safe and expeditious air traffic flow. The TCAS traffic display does not provide the information necessary for the provision of separation and sequencing. Manoeuvres initiated solely on the information shown on the TCAS traffic display have often degraded flight safety. Therefore, pilots must not attempt to self-separate nor to challenge an ATC instruction based on the information derived solely from the TCAS traffic display. It is the controllers' responsibility to separate aircraft. TCAS II will trigger an RA if there is a risk of collision between aircraft. A principle of TCAS II operation is that correct reaction to posted RAs will safely resolve such situations.

[24] EUROCONTROL ACAS II Bulletin No 6

3.2 Vertical maneuver to remain well clear of a single threat/intruder

3.2.1 Function Description

The TCAS Vertical Maneuver – Self Separation function uses the relative position, altitude and vertical trend indication (climbing/descending arrow) on the traffic display to climb/descend through another aircraft's altitude while maintaining a safe distance away from it. By utilizing the TCAS traffic display, a climb/descend strategy is implemented when the pilot determines there is a threat.

A UAS pilot needs to consider the following when making a decision:

1. Knowledge of intruders historical trend as displayed
2. Bearing indicated on the display may have large errors (peak error ±27º).
3. Estimated time to CPA.
4. Estimated lateral separation and vertical separation at CPA.
5. UAS performance limitations (e.g. turning performance) at present altitude.
6. Potential intent of intruder (e.g. ATC clearance and instructions)
7. Airspace in which UAS is operating (e.g. potential closing speeds)
8. Traffic that may not be displayed on TCAS display (not transponder equipped)

3.2.2 Assumptions used in this analysis

1. TCAS is operated in TA only mode
2. If a TA is received, the UAS pilot will not maneuver
3. If the UAS pilot is instructed by ATC not to maneuver, the UAS pilot will comply
4. No other displayed traffic information is available to the pilot (e.g., radar display, ADS-B display)
5. Information latency will not degrade safety of maneuver
6. TCAS will be operated in a continuous traffic display mode
7. The UAS pilot will only use vertical maneuvers to achieve vertical separation when the pilot has determined a threat
8. Specialized TCAS maneuver training including vehicle specific performance limitations is required
9. UAS are authorized to maneuver using the TCAS display

3.2.3 Scenario Description

To illustrate the exposed hazard, this paper develops a nominal scenario. The intent of presenting a scenario is not to represent all conditions under which the hazard is exposed, but to generally outline example conditions under which operations would be expected within the NAS. The scenario is exemplary of the "system state" where the worst credible hazard might be exposed. Many other scenarios would be possible within each system state. See the PHA tables developed in Appendix G for a complete assessment of all airspaces.

In the example scenario for this function, the ownship UAS is traveling from north to south (HDG-180) with a potential conflict at 1200 ft above the UAS and descending at approximately two o'clock displayed on the TCAS traffic display as traffic. The UAS is on an IFR Flight Plan. The following thought and decision process is followed by the UAS pilot.

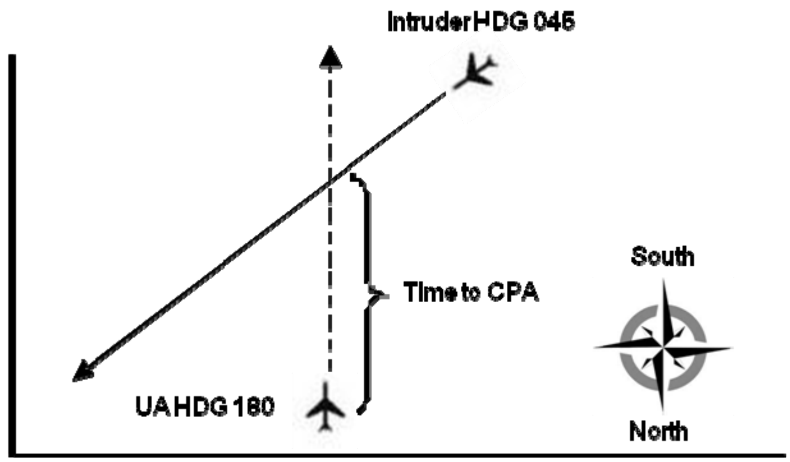

Figure 11 – Plan view – Vertical Maneuver for Self-Separation

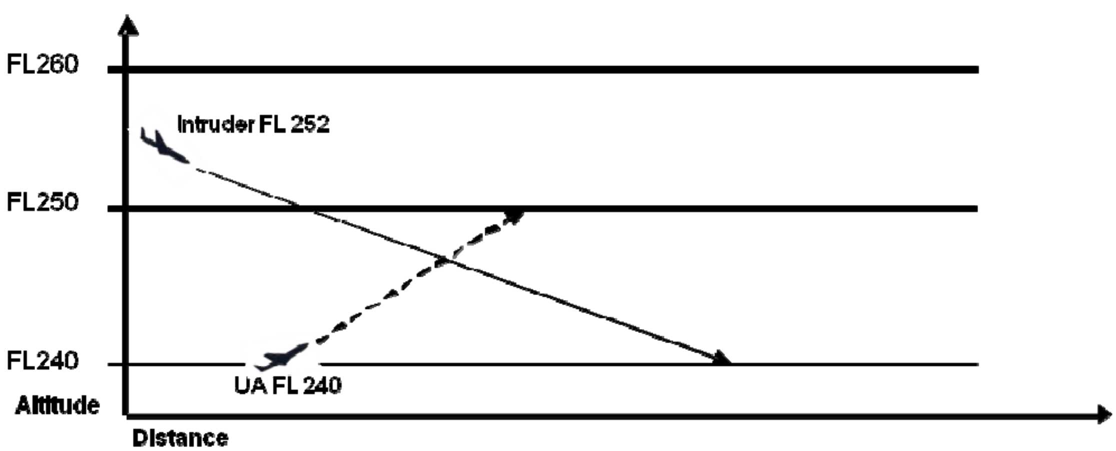

Figure 12 – Profile view – Vertical Maneuver for Self-Separation

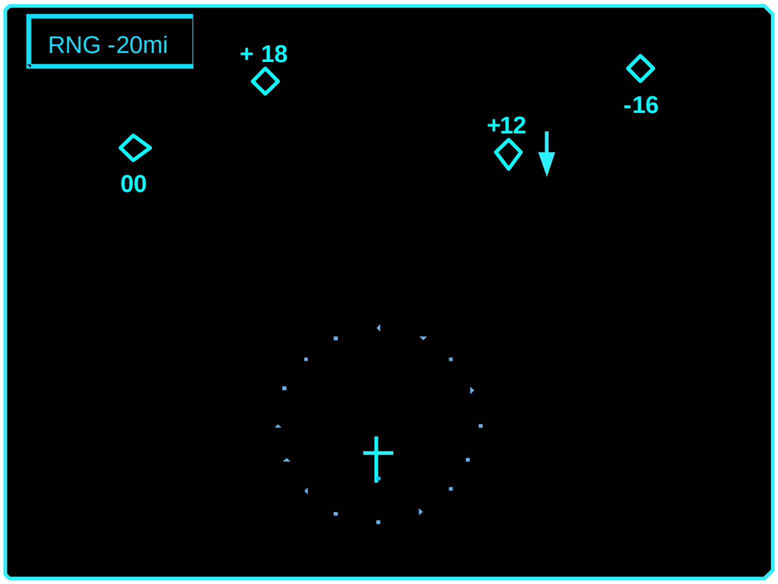

Figure 13 – TCAS Display for Vertical Maneuver

1. Detect traffic. The UAS pilot incorporates TCAS display into instrument. During one scan, the pilot sees that traffic is displayed on TCAS and begins to monitor the intruder traffic.
2. State estimation and tracking. The UAS pilot is now continuously monitoring the intruder traffic to begin to develop a trajectory projection. During this tracking, the UAS pilot will change the TCAS display range to gain resolution to determine the distance to the intruder and to answer the following questions;
   a. Does the intruder appear to be closing with the UAS in range, or is it pulling away?
   b. What is the vertical rate of change of the intruder, if any? (If less than 500 FPM, there will be no trend arrow displayed.)
   c. Does the intruder bearing appear to be on an intersecting geometry?

In this example scenario the pilot has determined that the intruder aircraft is closing in range and descending which feeds into the trajectory projection.

3. Trajectory projection. Based on the steps above, over time, the UAS pilot has converted his iterative state estimation to a trajectory projection. Although bearing accuracy of the TCAS system has inherent errors, the primary information that the UAS pilot will use in his trajectory projection is range, range rate and vertical rate of change. Range, range rate, and vertical rate of change are estimated from the interpretation of the display and not directly available as numeric values from the display.

In this example scenario the pilot has determined that the intruder aircraft will pass within 1000 ft vertically and less than 6 miles horizontally.

4. Threat declaration. If the projection of the intruder aircraft will not intersect the UA's flight path (range and altitude) then the UAS pilot will consider the intruder not to be a threat. This will be an iterative process as the resolution of traffic and ability to detect relative motion at the 40 NM maximum display range of TCAS is less than it will be at a closer (e.g. 20 NM) display range. The pilot must initiate the maneuver at such a time that a TA is not issued by the ownship UAS TCAS (i.e. assured to remain well clear).

In this example scenario, the pilot estimates that the traffic is approximately 14 NM away and closing and estimates the intruder trajectory will be within 1000 ft vertically, and therefore declares it a threat that requires a maneuver.

5. Resolve. Upon determination that a threat exists, the UAS pilot will attempt to resolve the threat. The options to resolve the threat are:
    a. Do nothing-no maneuver necessary or allowed (if closer than the predetermined minimum maneuvering range or if instructed by ATC not to maneuver.
    b. Climb/descend. If the UAS pilot calculates that a maneuver is warranted, he will initiate a climb or descent depending on the result of his trajectory projection in item 3 above. The UAS pilot will climb or descend at a rate that will not initiate or trigger a TA on ownship UAS TCAS, and will initiate the minimum altitude change to provide for self separation.

In this example scenario, the UAS pilot will climb at 1500 FPM to pass above the intruder traffic and end the climbing maneuver once achieving vertical separation to be well clear.

6. Execute climb. The UAS pilot will send a command to the UAS to execute a climb, and will inform ATC that they are "UAS Global View 123, initiating a climb on TCAS displayed traffic".

Upon completion of the successful separation maneuver and subsequent passing of the target traffic, the UAS pilot will inform ATC that they are clear of traffic and returning to their last assigned altitude unless otherwise directed by ATC.

3.2.4 Development of a Preliminary Hazard Analysis

Any maneuver for the purpose of maintaining self separation may result in the hazardous effect of "loss of separation" and potentially resulting in the need to perform a collision avoidance maneuver to avoid a mid-air collision. The complete PHA analysis can be found in Appendix G.

The hazard is exposed when the pilot makes an incorrect self-separation maneuver by:
- Initiating a climb maneuver

  - Change of climb rate
- Initiating a Descent maneuver
  - Change of descent rate
- Leveling off from a previous climb / descent
- Remaining on a level heading when a climb / descent was required

The causes of the hazard stem from pilot state estimation and interpretation errors as well as from equipment and display errors.

The first cause comes from errors in the pilot's ownship UAS state estimation. Since all of the state variables are directly readable from the pilot's PFD, the principal concern is latency of displayed information, pilot workload issues or distractions, and possibly differences in the pilot's perspective (the pilot being on the ground and not experiencing real flight).

The second cause comes from errors in the pilot's estimation of the intruder's state variables. From Table 3 (State Estimate Variables), the pilot must monitor the TCAS display for several seconds to track the intruder's azimuth and range, and must estimate a rough trajectory projection. Given the trajectory appears to be an intersecting geometry; he must estimate how long it will take to reach CPA with the intruding aircraft. With this time-to-CPA estimate, the pilot must further project the intruder's likely change in altitude based on currently displayed altitude and vertical trend indicator. He must also project his ownship UAS altitude based on his flight instruments. Finally, the pilot must speculate as to the other pilot's intent (the intruder might change course according to his flight plan or traffic pattern; he might see and avoid).

The third cause comes from possible equipment errors and algorithm limitations. TCAS errors generally stem from system limitations and include; imprecise azimuth resolution (position), reduced tracking accuracy and symbol placement during a maneuver, and limited display resolution for the intruder's vertical trend. Other intruder errors could cause ownship UAS TCAS to misrepresent the relative altitude (e.g. a data fault or altimeter fault). UAS equipment errors could also generate misrepresentations in the PFD for altitude, airspeed, heading, or flight path. Latency of the displayed data also introduces errors because the actual position of the intruder has already changed. Some equipment errors can be detected by the pilot or ATC, providing effective procedural control for some errors.

A fourth cause comes from uncooperative intruders (e.g. an intruder with no transponder or failed transponder) which may be missing from the display.

The system state is predominantly expressed by class of airspace. The sections which follow assess the worst credible outcome for each class.

3.2.5 Results/Observations

Performing a vertical maneuver using the TCAS traffic display is not acceptable in Class A, B, C, D, E and G airspace, based on the PHA which indicates the risk is high and fails the acceptance criteria. The traffic display may introduce substantial errors in estimating intruder state (e.g. position, velocity), projections of intruder future state and collision risk could be introduced by limitations in the TCAS traffic display and associated data. This could result in an incorrect vertical maneuver resulting in a loss of self separation, require a collision avoidance maneuver, or result in a mid-air collision. Additionally, sufficient operational mitigations have not been identified which would reduce the risk of the TCAS vertical maneuver in any airspace to an acceptable level.

3.3 Traffic Situation Awareness

TCAS provides a display of transponder equipped aircraft for which TCAS has established a track and satisfies the display criteria. The pilot's awareness of traffic in proximity of the UA is termed "traffic situation awareness". The TCAS traffic display provides limited information regarding transponder equipped aircraft in the vicinity of the UAS, but without identification of its limitations for providing Situation Awareness. Methods of providing situation awareness to any third parties (e.g. other aircraft or Air Traffic Control) are not considered.

3.3.1 Concept of Use

TCAS is installed on the UAS for the purpose of providing traffic information to establish situation awareness to the UAS pilot. The pilot would estimate the range, bearing, relative altitudes and vertical trends of displayed traffic in addition to the threat level depicted by the TCAS traffic symbology (TA, proximate or other traffic).

The traffic display would be used by the UAS pilot to form a traffic picture in concert with controller advisories. However, unlike manned aircraft TCAS installations, the flight crew cannot use to the traffic display to supplement the out-the-window view. The traffic information would be used solely to establish awareness of the traffic in proximity of the UA. The pilot would not use the information for any maneuvering of the UA.

TAs, in manned aircraft, are provided to alert the pilot to impending threats and to assist in visual acquisition of these potentially threatening aircraft. Thresholds for the TA vary based on the TCAS sensitivity level (altitude dependent), and the thresholds are designed with the intent of timely alerting the pilot to a threat. The alert criteria are not tied to separation standards. While manned aircraft pilots can use the TA to visually acquire traffic, UAS pilots are unable to visually acquire traffic and can only use the TA to enhance the situation awareness.

3.3.2 Assumptions used in this analysis

1. TCAS is operated in TA only mode
2. No other displayed traffic information is available to the pilot (e.g., radar display, ADS-B display)
3. Other aircraft may or may not be transponder equipped
4. TCAS will be operated in a continuous traffic display mode
5. Appropriate cautions and warnings are placarded to the display to specify limitations and inaccuracies of the presented traffic information

3.3.3 Observations

The TCAS II traffic display was designed to provide pilots with situation awareness of nearby, transponder equipped aircraft to support three specific functions:

1. Aid in the visual acquisition of traffic and differentiation of intruder threat levels.
2. Provide situational awareness.
3. Instill confidence in the displayed resolution advisories (RA).

The traffic information provided to support those functions is considered necessary and sufficient information to establish situation awareness for those specific functions and establishes the basis for display requirements to provide for them. This highlights the notion that the method of providing traffic information for situation awareness must be viewed in the context in which the pilot would use the information for actions or decisions. The display of traffic information for the purpose of situation awareness must specify how the traffic awareness would be used to facilitate action or as a decision support tool in order to identify and evaluate hazards resulting from its use. Otherwise, if there is vagueness or ambiguity regarding the use of the awareness provided through the display of traffic information, its installation and use cannot be substantiated by safety assessment.

The TCAS traffic display, in general terms, does not provide necessary and sufficient information to establish a complete and accurate awareness of the traffic situation in the proximity of the UA for functions beyond cuing the pilot for increased vigilance in visual acquisition and to prepare the pilot for an impending RA . The information provided on the TCAS traffic display also lacks supplemental information regarding its limitations and inaccuracies for the pilot's use when formulating traffic situation awareness.

The display has design limitations in providing sufficient information for the pilot to estimate intruder state and the pilots' projection of intruder state into the near future. Information not provided on the display, but essential in developing an accurate assessment of the traffic situation include, but are not limited to the following:

- All aircraft in the proximity of the UA may not be depicted on the display
- Aircraft depicted on the display may not represent their true locations
- Displayed traffic information represents a snapshot and may be delayed by several seconds
- Other aircraft may be responding to a TCAS RA
- Other aircraft may be maneuvering based on visual acquisition
- Other aircraft may be maneuvering in response to Air Traffic clearances or instructions
- Intruder altitudes may be unverified
- Intruder distance from ownship UAS are not provided directly on the display
- Intruder vertical rates are not indicated on the TCAS traffic display
- Intruder vertical trend indication would not be provided for vertical rates less than 500 FPM
- Intruder speeds are not indicated on the TCAS traffic display
- Intruder heading is not indicated on the TCAS traffic display
- The inaccuracies of TCAS display increase when in turns, climbs or descents

The above factors result in limitations of the traffic display in providing situation awareness. In addition to these, there are also human performance considerations. For example, reading altitude tags and constructing mental models of 4-dimensional relative trajectories from quick glances at the traffic display are difficult tasks for pilots, and prone to interpretation errors.

The FAA, Massachusetts Institute of Technology (MIT) Lincoln Laboratory and the Department of Transportation Volpe Center conducted a human factors study to determine what impact new TCAS symbology would have on pilot performance during TCAS events. An unexpected byproduct of this study was that:

> "Although pilot maneuvering was not the focus of this study, the results indicate pilots did maneuver in response to the TA… However, some maneuvering was observed in one third of all encounters, and eye tracking data suggests that the maneuvering decisions may have been influenced by traffic display information… Additionally, in one of the cases of horizontal maneuvering, the pilot induced a second RA by turning rapidly back into the intruder once the pilot thought he was clear of the conflict."[25]

This evidence demonstrates how the compelling nature of the TCAS traffic information entices pilots to maneuver based on the displayed traffic information, despite operational guidance and training to the contrary, even when afforded the ability to visually acquire potentially conflicting traffic. Without the ability to validate the presence, location, or other state information about an intruder that the pilot perceives as a threat, it is reasonable to assume that the UAS pilot could also be enticed into maneuvering based solely on the traffic display.

The risk of maneuvering for the purpose of self-separation has been determined by Hazard Analysis to be High risk (see appendices F and G). The TCAS display does not present critical information on intruders which is necessary for a pilot to establish an accurate and complete representation of the traffic situation. The compelling nature of the TCAS display could entice the UAS pilot to maneuver, regardless of any placarded limitations, training, or other prohibitions established against maneuvering.

Given that:

- maneuvering based on the TCAS display exposes High risk
- there is currently no means for the UAS pilot to independently validate the accuracy of the TCAS display
- the compelling nature of the display could entice the UAS pilot to maneuver

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[25] Impact of Traffic Symbol Directional Cues… Kaliardos, IEEE paper

- displayed traffic information does not provide necessary and sufficient information to establish a complete and accurate awareness of the traffic situation in the proximity of the UA for functions beyond cuing the pilot for increased vigilance in visual acquisition or to prepare the pilot for an impending RA
- the method for using the display of traffic information for the general purpose of situation awareness does not specify how the traffic awareness would be used to facilitate action or as a decision support tool in order to identify and evaluate hazards resulting from its use

The installation and use of TCAS for providing traffic information for the purpose of Situation Awareness should be prohibited.

4 Observations, Findings, and Conclusions

4.1 Observations

- TCAS was developed as a last resort airborne collision avoidance system
- TCAS includes a traffic display designed to cue pilots where to look out the window to visually acquire potentially conflicting airborne traffic in order to see and avoid them
- The proposed functions, which require defined methods of implementation for TCAS on UAS, are collision avoidance, self separation, and situation awareness
- The TCAS MOPS and TSO do not specifically cover the distributed architecture, and other issues necessary for proper installation and operation of TCAS on UAS
- The TCAS system is not an alternate means of compliance, nor is it a means of partial compliance, with 14 CFR 91.111 and 91.113 to see and avoid and to remain well clear of other aircraft
- Aircraft performance characteristics (e.g. climb, descent, bank angle limitations, etc) and data link capabilities (e.g. delays, availability, bandwidth, etc.) could dramatically degrade the safety and efficacy of the methods to perform the candidate functions; however, they were excluded from consideration in the analyses
- In order to properly evaluate new proposed methods of implementation and intended functions, the applicant must have a well developed, clearly defined, and mature CONOPS. This report documents a qualitative analysis because of a lack of data. An applicant is free to perform a quantitative analyses and make a case for their proposed method and/or function.

4.2 Findings:

- The TCAS display is subject to large discrepancies between intruder locations as presented on the traffic display versus their true locations

- The TCAS display lacks fundamental information about specific state parameters such as intruder range (specifically a numerical display), vertical rate, heading, closure rate, and time to CPA
- The TCAS display lacks the ability to project future states of the intruder. Trajectory information must be estimated by a pilot's sampling of traffic trends on the display over time
- In environments where transponding is not required, non-transponding aircraft will not appear on the TCAS display
- For manned aircraft, maneuvers based solely on a TA or on information displayed on the traffic display are not authorized. Some studies of TCAS display use by pilots have concluded that a significant proportion of experienced pilots misuse the information and initiate maneuvers based on TAs
- The information presented on the TCAS traffic display provides inadequate information to establish situation awareness of the traffic situation
- Performing a horizontal maneuver using the TCAS traffic display for self separation is high risk in Class A, B, C, D, E, and G airspace
- Performing a vertical maneuver using the TCAS traffic display for self separation is high risk in Class A, B, C, D, E, and G airspace
- No mitigations could be identified which would reduce the risk of performing a horizontal or vertical maneuver to an acceptable level
- The use of the TCAS display for pilot situation awareness does not present a risk as long as the information is not used as a basis for maneuvering
- The potential for misuse of the TCAS by a remote pilot presents an unacceptable risk

4.3 Conclusions:

- Performing a horizontal maneuver using the TCAS traffic display for self separation is unsafe in Class A, B, C, D, E, and G airspace
- Performing a vertical maneuver using the TCAS traffic display for self separation is unsafe in Class A, B, C, D, E, and G airspace.
- The representation of the traffic situation is inaccurate, potentially incomplete, misleading, and would be unsafe when used as the sole basis for maneuvering.

Use of TCAS on an UAS provides a compelling opportunity for misuse of the displayed information and should not be allowed.

5 Follow on Work

Currently, there is a broad range of work being conducted that may facilitate the use of TCAS on UAS. However, UAS use in the NAS will continue to be restricted until several high level problems such as command and control link vulnerabilities and see and avoid are resolved. The use of TCAS on UAS may, or may not, provide part of the solution.

TCAS could be integrated, either in total or in some modified form, as a component in a proposed SAA system. This would require defining architectures suitable to UAS design limitations and analysis of the TCAS allocation in such architectures by system safety assessment. It is difficult, however, to speculate how the TCAS system, its components or its surveillance data might be integrated into a larger SAA implementation. Components of the TCAS system that may contribute to an SAA implementation with potential areas identified as deficiencies in the PHA are described below.

These recommendations are areas where significant work and research are needed in order to successfully implement all or parts of TCAS on UAS in the near future.

Antenna Geometry

All TCAS installations require multiple antennas be placed on the aircraft; this may be a constraint for smaller UA. Any change to the minimum antenna separation and geometry based on characteristics of a specific UAS installation may result in unanticipated effects which have not been modeled or tested. If outside the TSO, this would require validation prior to certification. Modeling and simulation should be conducted to determine if an optimized antenna array may result in enhanced bearing accuracy.

Bearing Accuracy

TCAS III was an attempt to enhance the capabilities of TCAS II by providing additional threat resolution in the horizontal plane. This attempt was abandoned when it was found that TCAS III's ability to resolve encounters in the horizontal plane was limited by the accuracy in the estimation of the intruder's bearing rate during an encounter. The degree of uncertainty in the horizontal miss distance estimate is directly related to the bearing rate error and the bearing measurements can contain relatively large errors due to limitations in the antenna subsystem.[26] The bearing measurement errors are introduced by electromagnetic scattering of the airframe and nearby objects, and result in large errors in the miss distance estimation.[27] More research is needed to improve TCAS bearing accuracy.

RF Environment

Today's UAS are airborne platforms for a variety of sensors which impact the RF environment and may degrade TCAS system performance. These potential issues will require further analysis.

TCAS Architecture

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[26] TCAS Maneuvering Aircraft in the Horizontal Plane, Burgess

[27] TCAS III Bearing Error Evaluation, Burgess

The TCAS Minimum Operational Performance Standard and Technical Standard Order do not provide for a distributed architecture which would be needed if TCAS is employed on a UAS. Various architectures and configurations would need to be analyzed and studied.

Automation
Architectures should ensure minimum system and control link latency, and reduce reliance on unreliable or reduced availability control links. Studies on automated responses to TCAS should be considered in the architecture choices to counter the effects of unreliable control links.

Autonomy
Whether it is Pilot in the loop, Pilot on the loop, or Pilot out of the loop, the level of UAS autonomy will have a great effect on the architecture of all systems. Additional research, development, modeling and simulation is needed in this area.

Data Information Interface and Human Factors
Some basics questions about human-machine interface need to be answered. At a minimum, the question of the traffic display and its ability to transfer meaningful, actionable and correct information to the human counterpart needs to be addressed. Formulating the appropriate analytical questions, followed by Human In The Loop (HITL) modeling and simulation should be conducted. The question as to whether the information should be informative (i.e. Standard Terminal Automation Replacement System (STARS)), or directive (i.e. TCAS Resolution Advisory Display) must also be addressed.

Control Link Latency
Modeling and simulation of the latency of the control link in various TCAS on UAS installation architectures should reflect all available control links and their various configurations. This should be used to bound both the maximum latency permissible and define the potential range limitations for using TCAS on UAS. Modeling and simulation should be conducted to determine what latency value induces TAs or RAs to determine the impact of latency on risk ratio and ultimately safety, using encounter geometries unique to UAS missions. Identification of maximum permissible latency prior to reaching an unacceptable risk ratio may be used to determine how TCAS-equipped UAS may be safely flown.

Control Link Reliability and Availability
Additional study and research is needed to mitigate the negative effects of the lack of control link availability and reliability. This could be characterized as a degraded ability for TCAS to display other aircraft position accurately and the additional degraded capability of the UAS pilot to issue flight commands to the UAS. Whatever the outcomes, control link availability and reliability represents a serious hurdle to the acceptance of UAS operations in the NAS.

UAS Performance Requirements

TCAS was designed for transport category, jet powered aircraft and may not accurately reflect the performance characteristics of UAS. Modeling and simulation should be used to determine the effective limit to the kinds and numbers of performance inhibitions that can be introduced to TCAS for UAS applications.

1030/1090 MHz Frequency Congestion

Rapid increase in the total number of transponder equipped aircraft, both manned and unmanned, may cause excessive frequency congestion and degradation in the effectiveness of TCAS on manned aircraft. Modeling and simulation of an increased number of TCAS systems (both low and high altitude) should be conducted to determine the potential safety degradation due to frequency congestion. This should include modeling and simulation to determine the impact of an increase in the signal propagation footprint based on high altitude flight and how that might increase 1030/1090 saturation.

Appendix A Acronyms and Glossary

Acronym	Definition or Description
AC	Advisory Circular
ACAS	Airborne Collision Avoidance System
ADC	Air Data Computers
ADS-B	Automatic Dependent Surveillance-Broadcast
AEEC	Airlines Electronic Engineering Committee
AFM	Airplane Flight Manual
AFS	Aircraft Flight Standards
Airworthiness	The aircraft conforms to its type design and is in a condition for safe flight[28]
ASI	Air Speed Indicator
ATC	Air Traffic Control
ATC Separation Services	A service provided for the purpose of:[29] 1. Preventing collisions: a. Between aircraft; and b. On the maneuvering area between aircraft and obstructions 2. Expediting and maintaining an orderly flow of air traffic
ATO	Air Traffic Organization
Bow-Tie Model	A structured approach in which causes of hazards are directly linked to possible outcomes or effects in a single diagram[30]
BRITE	Brite Radar Indicator Tower Equipment
CFR	Code of Federal Regulations
CHG	Change
Civil Aircraft	All non-public aircraft, both private and commercial
Closest Point of Approach	As computed from a threat's range and range rate[31]
Collision Avoidance	The action, independent of ATC separation services, where a UAS maneuvers to prevent penetration of the collision volume[32]
Collision Volume	A cylindrical volume of airspace centered on the UA with a horizontal radius of 500 ft and a vertical height of 200 ft (± 100 ft) within which avoidance of a collision can only be considered a matter of chance
CPA	Closest Point of Approach
EATCHIP	European Air Traffic Control Harmonization and Integration Program
EICAS	Engine Indication and Crew Alerting System

[28] 14 CFR Part 3

[29] 7110.65T

[30] ATO Safety Management System Manual

[31] Introduction to TCAS II, Version 7

[32] SAA Workshop Final Report

Encounter	The interval of time that any intruder remains on the TCAS display and the pilot performs state estimates and trajectory projections with respect to ownship
FAA	Federal Aviation Administration
FL	Flight Level
FMS	Flight Management System
FPM	Feet Per Minute
Function	The specific process, action or task that a system is designed to perform
GCS	Ground Control Station
GPS	Global Positioning System
HDG	Heading
HITL	Human In The Loop
HSI	Horizontal Situation Indicator
HUD	Heads-Up Display
IAW	In Accordance With
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
INS	Inertial Navigation System
Intended Function	The ability for the equipment and aircraft combination to perform the operation, and meet the requirements for which the system was designed[33]
Intruder	A transponder equipped aircraft within the surveillance range of TCAS for which TCAS has an established track.
IVSI	Instantaneous Vertical Speed Indicator
Likelihood Classification	An expression of how often it is expected that the resulting harm will occur at the worst credible severity[34]
Lost Link	The loss of communication between a Unmanned Aircraft System and a Ground Control Station
Method	Various means and implementations for conceptual uses of TCAS supporting decisions and any resulting actions to accomplish a candidate function
MFD	Multi Function Display
MIT	Massachusetts Institute of Technology
Mode C Transponder	ATC transponder that replies to an interrogation containing a 4-digit code assigned by ATC and the aircraft's pressure altitude
Mode S Transponder	ATC transponder that replies to an interrogation containing its own, unique 24-bit selective address, and typically with altitude data[35]
MOPS	Minimum Operational Performance Specification
MSL	Mean Sea Level
NAS	National Airspace System
NM	Nautical Mile

[33] AC 20-138B

[34] ATO Safety Management System Manual

[35] Introduction to TCAS II, Version 7

PANS-ATM	Procedures for Air Navigation Services – Air Traffic Management
PANS-OPS	Procedures for Air Navigation Services – Aircraft Operations
PFD	Primary Flight Display
PHA	Preliminary Hazard Analysis
Pilot Determined Threat	Any intruder on the TCAS display which causes the UAS pilot a higher level of concern as a potential loss of separation or mid-air collision risk
Preliminary Hazard Analysis	Provide an initial overview of the hazards present in the overall flow of the operation[36]
Pressure Altitude	The indicated altitude when an altimeter which is set to the baseline pressure setting of 29.92 inches of mercury
Public Aircraft	An aircraft operated by or on behalf of the United States Government[37]
RA	Resolution Advisory
Resolution Advisory	Resolution advisory. An indication given by TCAS II to a flight crew that a vertical maneuver should, or in some cases should not, be performed to attain or maintain safe separation from a threat[38]
RF	Radio Frequency
RTCA	Radio Technical Commission for Aeronautics
RVSM	Reduced Vertical Separation Minimum
SAA	Sense and Avoid
Safety Management System	Provides a systematic and integrated method for managing the safety of ATC and navigation services in the NAS[39]
Safety Risk Management	The processes and practices used to assess changes to the NAS for safety risk, the documentation of those changes, and the continuous monitoring of the effectiveness of any controls used to reduce risk to acceptable levels[40]
SARPs	Standards and Recommended Practices
Self Separation	The action independent of ATC separation services where a UAS maneuvers to maintaining well clear, while conforming to accepted right of way rules[41]
Sense and Avoid	The capability of a UAS to remain well clear from and avoid collisions with other airborne traffic. SAA provides the functions of self separation and collision avoidance to fulfill the regulatory requirement to "see and avoid"[42]
Separation	The spacing of aircraft to achieve their safe and orderly movement in flight and while landing and taking off[43]

[36] ATO Safety Management System Manual

[37] Section 40102(a)(37) of title 49, United States Code

[38] Introduction to TCAS II, Version 7

[39] ATO Safety Management System Manual

[40] ATO Safety Management System Manual

[41] SAA Workshop Final Report

[42] SAA Workshop Final Report

[43] 7110.65T

Service	A generic term that designates functions or assistance available from or rendered by air traffic control[44]
Severity Classification	The measure of how bad the results of an event are predicted to be by determining the worst credible outcome[45]
SMS	Safety Management System
SRM	Safety Risk Management
Standard Terminal Automation Replacement System	Receives radar data and flight plan information and presents the information to air traffic controllers on high resolution, 20" x 20" color displays allowing the controller to monitor, control, and accept hand-off of air traffic.
STARS	Standard Terminal Automation Replacement System
TA	Traffic Advisory
TA-only mode	A TCAS mode of operation in which TAs are displayed when required, but all RAs are inhibited[46]
TCAS	Traffic Alert and Collision Avoidance System
TCAS I	Traffic Alert and Collision Avoidance System I is the first generation of collision avoidance technology. It is an airborne collision avoidance system based on radar beacon signals which operates independent of ground-based equipment. TCAS-I generates traffic advisories only[47]
TCAS II	Traffic Alert and Collision Avoidance System II is the second and current generation of collision avoidance technology. It is an airborne collision avoidance system based on radar beacon signals which operates independent of ground-based equipment. TCAS-II generates traffic advisories, and resolution (collision avoidance) advisories in the vertical plane[48]
TCAS III	Traffic Alert and Collision Avoidance System III was to be the third generation of collision avoidance technology but has been canceled. It was an airborne collision avoidance system based on radar beacon signals which operates independent of ground-based equipment. TCAS-III attempted to generate resolution advisories in the vertical and horizontal plane.
Threat	A target that has satisfied the threat detection logic and thus requires a resolution advisory
Traffic Advisory	An indication given by TCAS to the pilot when an aircraft has entered, or is projected to enter, the protected volume around the own aircraft[49]
Transponder	A receiver/transmitter which will generate a reply signal upon proper interrogation; the interrogation and reply being on different frequencies[50]

[44] 7110.65T

[45] ATO Safety Management System Manual

[46] Introduction to TCAS II, Version 7

[47] 7110.65T

[48] 7110.65T

[49] Introduction to TCAS II, Version 7

[50] 7110.65T

TSO	Technical Standard Order
UA	Unmanned Aircraft
UAPO	Unmanned Aircraft Program Office
UAS	Unmanned Aircraft System
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VSI	Vertical Speed Indicator
Well Clear	The state of being able to maintain a safe distance from other aircraft so as not to cause the initiation of a collision avoidance maneuver in either aircraft[51]

[51] SAA Workshop Final Report

Appendix B Bibliography

i) RTCA Standards
   a. DO-185B, Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II) Version 7.1 Volume I, RTCA June 2008
   b. DO-298, Safety Analysis of Proposed Change to TCAS RA Reversal Logic, RTCA November 2005

ii) 14 Code of Federal Regulations (CFR)
   a. 3, General Requirements
   b. 25, Airworthiness Standards: Transport Category Airplanes
   c. 91.111, Operating near other aircraft
   d. 91.113, Right-of-way rules: Except water operations
   e. 91.126, Operating on or in the vicinity of an airport in Class G airspace
   f. 91.127, Operating on or in the vicinity of an airport in Class E airspace
   g. 91.129, Operations in Class D airspace
   h. 91.130, Operations in Class C airspace
   i. 91.131, Operations in Class B airspace
   j. 91.135, Operations in Class A airspace
   k. 91.215, ATC Transponder and Altitude Reporting Equipment and Use
   l. 121, Operating Requirements: Domestic, Flag, Supplemental operations
   m. 125, Certification and Operations: Airplanes Having a Seating Capacity of 20 or More Passengers or a Payload Capacity of 6,000 Pounds or More
   n. 129, Operations: Foreign air carriers and foreign operators of U.S. registered aircraft engaged in common carriage
   o. 135, Operating requirements: Commuter and on demand operations and rules governing persons on board such aircraft

iii) FAA Orders
   a. 7210.56C chg2, Air Traffic Quality Assurance, July 2009
   b. 7110.65T, Air Traffic Control, February 2010

iv) FAA Advisory Circulars
   a. AC 20-151A, Airworthiness Approval of Traffic Alert And Collision Avoidance Systems (TCAS II), Versions 7.0 & 7.1 and Associated Mode S Transponders, September 2009
   b. AC 20-131a, Airworthiness Approval of Traffic Alert And Collision Avoidance Systems (TCAS II) and Associated Mode S Transponders, April 1999
   c. AC 25.1309-1A, System Design and Analysis, June 1988
   d. AC 120-55B, Air Carrier Operational Approval and Use of TCAS II, October 2001

v) FAA Technical Standard Orders (TSO)
   a. TSO C-119c, Traffic Alert and Collision Avoidance System (TCAS) Airborne Equipment, TCAS II with Optional Hybrid Surveillance, April 2009

vi) Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS), FAA Sponsored “Sense and Avoid” Workshop Final Report, October 2009

vii) Air Traffic Organization (ATO) Safety Management System Manual (SMS) Version 2.1 May 2008

viii) Aeronautical Information Manual (AIM) Official Guide to Basic Flight Information and ATC Procedures, FAA, February 2010

ix) Pilot’s Handbook of Aeronautical Knowledge, FAA-H-8083-25A, 2008

x) Introduction to TCAS II, Version 7, US Department of Transportation, Federal Aviation Administration November 2000

xi) TCAS: Maneuvering Aircraft in the Horizontal Plane, Burgess, Lincoln Laboratory Journal Volume 7 Number 2, 1994

xii) TCAS III Bearing Error Evolution, Burgess, MIT Lincoln Laboratory ATC-231, 1995

xiii) EUROCAE ED-143, Vol. I: MOPS for Traffic Alert and Collision Avoidance System II (TCAS II)

xiv) ICAO Standards and Recommended Practices
   a. PANS-OPS Document 8168, 2006
      i. Volume 1 - Flight Procedures
      ii. Volume 2 - Construction of Visual and Instrument Flight Procedures

b. PANS-ATM Document 4444, Rules Of The Air and Air Traffic Services

xv) ACAS Bulletin No6, Incorrect use of the TCAS traffic display, EUROCONTROL, March 2005

xvi) ARINC Characteristic 735A, Mark 2 Traffic Alert and Collision Avoidance System (TCAS), ARINC, Jan 2003

xvii) ARINC Characteristic 718A-3, Mark 4 Air Traffic Control Transponder (ATCRBS/Mode S), ARINC, Jun 2010

xviii) National Transportation Statistics 2010, Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics, Table 2-15: Number of Pilot-Reported Near Midair Collisions (NMAC) by Degree of Hazard, October 2010

xix) 2008 Nall Report, Accident Trends and Factors for 2007, AOPA Air Safety Foundation, March 2008

xx) Design and Evaluation for Situation Awareness Enhancement, 97-101, Proceedings of the Human Factors Society 32nd Annual Meeting, Mica R. Endsley, 1988

xxi) Correlated Encounter Model for cooperative aircraft in the NAS Volume 1,_ATC-344,_Kochenderfer,_2008

xxii) Impact of Traffic Symbol Directional Cues on Pilot Performance During TCAS Events, Olson, Kaliardos, Zuschlag, Kendra, Digital Avionics Systems Conference IEEE, October 2009

xxiii) TCAS Maneuvering Aircraft in the Horizontal Plane, Burgess Lincoln Laboratory Journal, volume 7, number 2 1994

xxiv) ACAS Monitoring in the USA, Eurocontrol ACAS Downlink Monitoring Workshop, Briefing, MIT Lincoln Lab, October 2009

xxv) TOPA Overview (TCAS Operational Performance Assessment Program 2008), TCAS Technical Interchange Meeting, Briefing, MIT Lincoln Lab, August 2010

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Appendix D Traffic Advisory and Collision Avoidance System II (TCAS II)

D.1 Description

TCAS II provides traffic advisories and resolution advisories (RA), i.e., recommended escape maneuvers, in the vertical dimension to either increase or maintain the existing vertical separation between aircraft. Airline aircraft, including regional airline aircraft with more than 30 seats, and general aviation turbine-powered aircraft use TCAS II equipment.

TCAS is designed to work autonomously of the aircraft navigation equipment and independently of the ground systems used to provide ATC services. TCAS interrogates ICAO-compliant transponders of all aircraft in the vicinity and based on the replies received, tracks the slant range, altitude (when it is included in the reply message), and bearing of surrounding traffic. From several successive replies, TCAS calculates a time to reach the CPA (Closest Point of Approach) with the intruder, by dividing the range by the closure rate. This time value is the main parameter for issuing alerts. If the transponder replies from nearby aircraft includes their altitude, TCAS also computes the time to reach co-altitude. TCAS can issue two types of alerts:

- TAs to assist the pilot in the visual search for the intruder aircraft and to prepare the pilot for a potential RA; and

- RAs to recommend maneuvers that will either increase or maintain the existing vertical separation from an intruder aircraft. When the intruder aircraft is also fitted with TCAS II, both TCAS' coordinate their RAs through the Mode S data link to ensure that complementary resolution senses are selected.

TCAS II is designed to operate in traffic densities of up to 0.3 aircraft per square nautical mile (nmi), i.e., 24 aircraft within a 5 nmi radius, which is the highest traffic density envisioned over the next 20 years.

D.2 Components of a TCAS II

The major components of a TCAS II system are depicted by the block diagram in Figure 14.

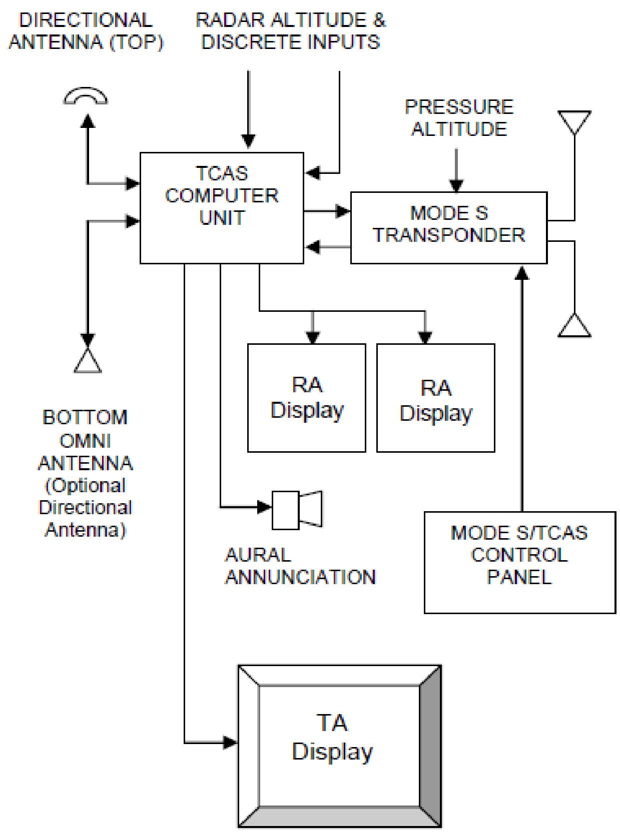


Figure 14 TCAS II Block Diagram

A TCAS II installation consists of the following major components.

D.2.1 TCAS Computer Unit

The TCAS Computer Unit, or TCAS Processor, performs airspace surveillance, intruder tracking, its own aircraft altitude tracking, threat detection, RA maneuver determination and selection, and generation of advisories. The TCAS Processor uses pressure altitude, radar altitude, and discrete aircraft status inputs from its own aircraft to control the collision avoidance logic parameters that determine the protection volume around the TCAS aircraft. If a tracked aircraft is a collision threat, the processor selects an avoidance maneuver that will provide adequate vertical miss distance from the intruder while minimizing the perturbations to the existing flight path. If the threat aircraft is also equipped with TCAS II, the avoidance maneuver will be coordinated with the threat aircraft.

D.2.2 Mode S Transponder

A Mode S transponder is required to be installed and operational for TCAS II to be operational. If the Mode S transponder fails, the TCAS Performance Monitor will detect this failure and automatically place TCAS into Standby. The Mode S transponder performs the normal functions to support the ground-based ATC system and can work with either an ATCRBS or a Mode S ground sensor. The Mode S transponder is also used to provide air-to-air data exchange between TCAS-equipped aircraft so that coordinated, complementary RAs can be issued when required.

D.2.3 Mode S/TCAS Control Panel

A single control panel is provided to allow the flight crew to select and control all TCAS equipment, including the TCAS Processor, the Mode S transponder, and in some cases, the TCAS displays. A typical control panel provides four basic control positions:

- **Stand-by**: Power is applied to the TCAS Processor and the Mode S transponder, but TCAS does not issue any interrogations and the transponder will reply to only discrete interrogations

- **Transponder**: The Mode S transponder is fully operational and will reply to all appropriate ground and TCAS interrogations. TCAS remains in Standby

- **TA Only**: The Mode S transponder is fully operational. TCAS will operate normally and issue the appropriate interrogations and perform all tracking functions. However, TCAS will only issue TAs, and the RAs will be inhibited

- **Automatic or TA/RA**: The Mode S transponder is fully operational. TCAS will operate normally and issue the appropriate interrogations and perform all tracking functions. TCAS will issue TAs and RAs, when appropriate

D.2.4 Cockpit Presentation

The TCAS interface with the pilots is provided by two displays ---- the traffic display and the RA display. These two displays can be implemented in a number of ways, including displays that incorporate both displays into a single, physical unit. Regardless of the implementation, the information displayed is identical. The standards for both the traffic display and the RA display are defined in DO-185A.

D.2.4.1 Traffic Display

The traffic display, which can be implemented on either a part-time or full-time basis, depicts the position of nearby traffic, relative to its own aircraft. It is designed to provide information that will assist the pilot in visual acquisition of other aircraft. If implemented on a part-time basis, the display will automatically activate whenever a TA or an RA is issued. Current implementations include dedicated traffic displays; display of the traffic information on shared weather radar displays, MAP displays, Engine Indication and Crew Alerting System (EICAS) displays; and other multifunction displays.

A majority of the traffic displays also provide the pilot with the capability to select multiple ranges and to select the altitude band for the traffic to be displayed. These capabilities allow the pilot to display traffic at longer ranges and with greater altitude separation while in cruise flight, while retaining the capability to select lower display ranges in terminal areas to reduce the amount of display clutter.

D.2.4.2 Traffic Display Symbology

Both color and shape are used to assist the pilot in interpreting the displayed information. Refer to Figure 15 for examples of the symbology. The own aircraft is depicted as either a white or cyan arrowhead or airplane-like symbol. The location of the own aircraft symbol on the display is dependent on the display implementation. Other aircraft are depicted using geometric symbols, depending on their threat status, as follows:

- An unfilled diamond, shown in either cyan or white, but not the same color as the own aircraft symbol, is used to depict non-threat traffic

- A filled diamond, shown in either cyan or white, but not the same color as the own aircraft symbol, is used to depict Proximate Traffic. Proximate Traffic is non-threat traffic that is within 6 nmi and +/- 1200 ft from own aircraft

- A filled amber or yellow circle is used to display intruders that have caused a TA to be issued

- A filled red square is used to display intruders that have caused an RA to be issued

Each symbol is displayed on the screen according to its relative position to own aircraft. To aid the pilot in determining the range to a displayed aircraft, the traffic display provides range markings at one-half the selected scale and at the full scale. Additional range markings may be provided at closer ranges, e.g., 2 nmi, on some display implementations. The selected display range is also shown on the display. The range markings and range annunciation are displayed in the same color as the own aircraft symbol unless the traffic display is integrated with an existing display that already provides range markings, e.g., a MAP display.

Vertical speed information and altitude information are also provided for all displayed traffic that are reporting altitude. Relative altitude is displayed in hundreds of feet above the symbol if the intruder is above own aircraft and below the symbol if the intruder is below own aircraft. When the intruder is above the own aircraft, the relative altitude information is preceded by a + sign. When the intruder is below the own aircraft, a --- sign precedes the relative altitude information. In some aircraft, the flight level of the intruder can be displayed instead of its relative altitude. The flight level is shown above the traffic symbol if the intruder is above the own aircraft and below the traffic symbol is the intruder is below the own aircraft. If the intruder is not reporting its altitude, no altitude information in shown for the traffic symbol. The altitude information is displayed in the same color as the aircraft symbol.

An arrow is displayed immediately to the right of a traffic symbol when the target aircraft is reporting its altitude and is climbing or descending at more than 600 fpm. An up arrow is used for a climbing aircraft; a down arrow is used for a descending aircraft. The arrow is displayed in the same color as the aircraft symbol.

When an aircraft causing a TA or RA is beyond the currently selected range of the traffic display, half TA or RA symbols will be displayed at the edge of the display at the proper relative bearing. In some implementations, a written message such as TRAFFIC, TFC, or TCAS is displayed on the traffic display if the intruder is beyond the selected display range. The half symbol or the written message will remain displayed until the traffic moves within the selected display range; the pilot increases the range on a variable range display to allow the intruder to be displayed; or the pilot selects a display mode that allows traffic to be displayed.

In some instances, TCAS may not have a reliable bearing for an intruder causing a TA or RA. Because bearing information is used for display purposes only, the lack of bearing information does not affect the ability of TCAS to issue TAs and RAs. When a "No-Bearing" TA or RA is issued, the threat level, as well as the range, relative altitude, and vertical rate of the intruder, are written on the traffic display. This text is shown in red for an RA and in amber or yellow for a TA. For example, if an RA was issued against an intruder at a range of 4.5 nmi and with a relative altitude of +1200 feet and descending, the "No Bearing" indication on the traffic display would be: RA 4.5 +12 ↓ Figure 15 shows the use of the various traffic symbology used on the traffic display.

D.2.5 Resolution Advisory Display

The RA display provides the pilot with information on the vertical speed or pitch angle to fly or avoid to resolve an encounter. The RA display is typically implemented on an instantaneous vertical speed indicator (IVSI); a vertical speed tape that is part of a Primary Flight Display (PFD); or using pitch cues displayed on the PFD. RA guidance has also been implemented on a Heads-Up Display (HUD). The implementations using the IVSI or a vertical speed tape use red and green lights or markings to indicate the vertical speeds to be avoided (red) and the desired vertical speed to be flown (green).
An implementation using pitch cues uses a unique shape on the PFD to show the pitch angle to be flown or avoided to resolve an encounter. HUD implementations also use a unique shape to indicate the flight path to be flown or avoided to resolve an encounter. In general, the round-dial IVSI implementation is used on the older nonglass aircraft. However, some operators have implemented this display in their glass aircraft to provide a common display across their fleet types. Some IVSI implementations use mechanical instruments with a series of red and green LEDs around the perimeter of the display, while other implementations use an LCD display that draws the red and green arcs at the appropriate locations. The LCD display implementations also

have the capability to provide both the traffic and RA display on a single instrument. On glass aircraft equipped with a PFD, some airframe manufacturers have implemented the RA display on the vertical speed tape; some have elected to provide pitch cues; and other implementations provide both pitch cues and a vertical speed tape.

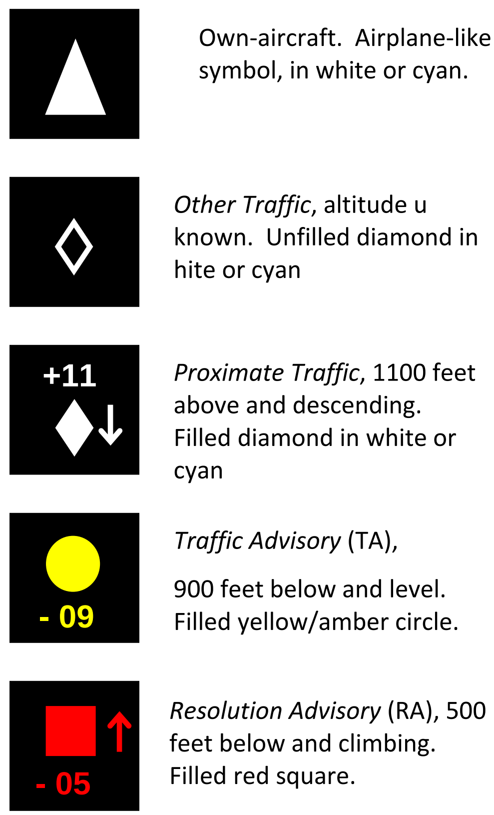
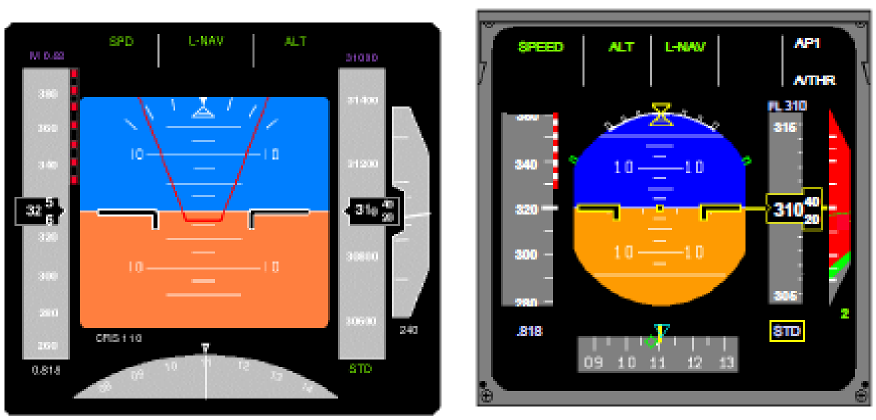


Figure 15 Standardized Symbology for Use on the Traffic Display

Figure 16 TCAS RA Display implemented on an IVSI



Pitch Cue Implementation   Vertical Speed Tape Implementation

Figure 17 TCAS RA Displays Implemented on a PFD

D.3 Target Surveillance

TCAS, independent of any ground inputs, performs surveillance of nearby aircraft to provide information on the position and altitude of these aircraft so the collision avoidance algorithms can perform their function. The TCAS surveillance function operates by issuing interrogations at 1030 MHz that transponders on nearby aircraft respond to at 1090 MHz. These replies are received and decoded by the surveillance portion of the TCAS software and the information is then provided to the collision avoidance algorithms. TCAS has a requirement to provide reliable surveillance out to a range of 14 nmi and in traffic densities of up to 0.3 aircraft per square nautical mile. The surveillance function provides the range, altitude, and bearing of nearby aircraft to the collision avoidance function so threat determinations can be made and so the information displayed on the traffic display is accurate. The TCAS surveillance is compatible with both the ATCRBS and Mode S transponders.

TCAS can simultaneously track at least 30 transponder-equipped aircraft within its surveillance range.

D.3.1 Interference Limiting

Interference limiting is a necessary part of the surveillance function. To ensure that no transponder is suppressed by TCAS activity for more than 2% of the time, and that TCAS does not create an unacceptably high fruit rate for the ground-based ATC radars, multiple TCAS units within detection range of one another, i.e., approximately 30 nmi, are designed to limit their own transmissions under certain conditions. As the number of such TCAS units within this region increases, the interrogation rate and power allocation for each of them must decrease to prevent undesired interference with the ATC radars.

D.3.2 Traffic Advisory Display

The functions of the traffic advisory display are to aid the flight crew in visually acquiring intruder aircraft; discriminating between intruder aircraft and other nearby aircraft; determining the horizontal position of nearby aircraft; and providing confidence in the performance of TCAS. Traffic advisory displays have been implemented in a number of different ways and with varying levels of flexibility. The requirements for the various means of implementing the traffic displays are documented in RTCA DO-185A.

Version 7 requirements inhibit the display of intruders with relative altitudes of more than ±9900 ft if the pilot has selected the display of relative altitude. This display range is the maximum possible because only two digits are available to display the relative altitude.

D.4 Requirements for World-Wide Carriage of TCAS II

The U.S. was the first ICAO member State to mandate carriage of an airborne collision avoidance system for passenger carrying aircraft operating in its airspace.

Because of this mandate, the number of long range aircraft being fitted with TCAS II and operating in European and Asian airspace continued to increase even though system carriage and operation was not mandatory in that airspace. As studies, operational experience, and evaluations continued to demonstrate the safety benefits of TCAS II, some non-U.S. airlines also equipped their short-haul fleets with TCAS.

In 1995, the EUROCONTROL Committee of Management approved an implementation policy and schedule for the mandatory carriage of TCAS II in Europe. The European Air Traffic Control Harmonization and Integration Program (EATCHIP) Project Board then ratified this policy. The approved policy requires that:

- From 1 January 2000, all civil fixed-wing turbine-powered aircraft having a maximum take-off mass exceeding 15,000 kg, or a maximum approved passenger seating configuration of more than 30, will be required to be equipped with TCAS II, Version 7.0

- From 1 January 2005, all civil fixed-wing, turbine-powered aircraft having a maximum take-off mass exceeding 5,700 kg, or a maximum approved passenger seating configuration of more that 19, will be required to be equipped with TCAS II, Version 7.0.

In the U.S. effective Jan 1, 2005, for those aircraft required to carry TCAS II, Version 7.0 or later must be installed in all new installations. For installations of TCAS II made prior to Jan 1, 2005 under certain conditions, Version 6.04a can continue to be used.

D.5 RVSM Considerations

With the creation of Reduced Vertical Separation Minimum (RVSM) airspace, a minimum requirement for TCAS equipage was established. Specifically, in order to operate an aircraft with TCAS II in RVSM airspace, it must meet TSO-C119b (Version 7.0) or a later version. In the US, operations outside RVSM airspace with TCAS II can be conducted using Version 6.04a.

D.6 Standards and Guidance Material

The data obtained from FAA and industry sponsored studies, simulations, flight tests, and operational evaluations have enabled RTCA to publish the MOPS for TCAS II. The current version of the MOPS, DO-185B, describes the standards, requirements, and test procedures for TCAS Version 7.1. EUROCAE ED-143 is the equivalent document for ACAS II.

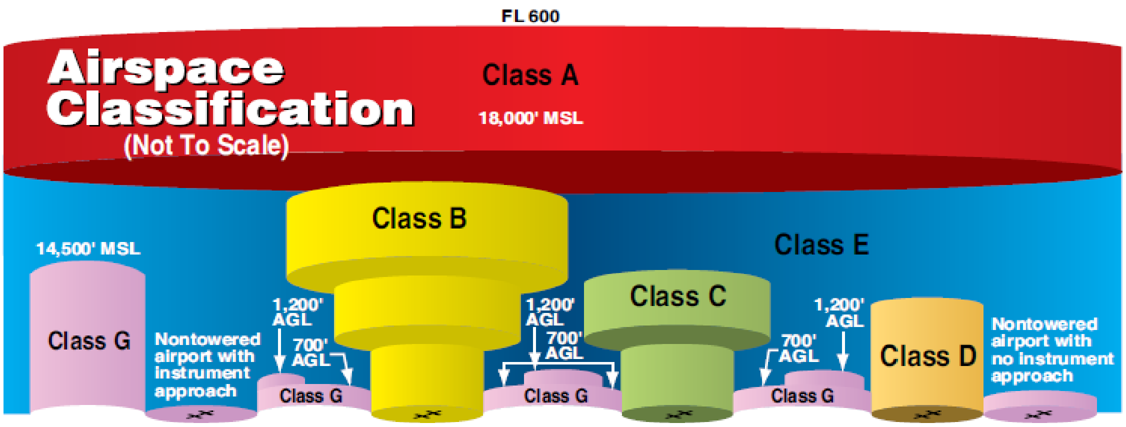
For TCAS II, TSO C119c and Advisory Circular 20-151A have been published for use by FAA airworthiness authorities in certifying the installation of TCAS II on various classes of aircraft. Advisory Circular 120-55C defines the procedures for obtaining air carrier operational approval for the use of TCAS II. While FAA developed these documents, they have been used throughout the world by civil aviation authorities to approve the installation and use of TCAS, or as the basis for development of State-specific requirements and guidance.

ICAO Standards and Recommended Practices (SARPs) and Guidance Material for ACAS I and ACAS II have been published in Annex 10. The procedures for use of ACAS have been published in PANS-OPS Document 8168 and guidance to air traffic controllers, along with the phraseology for reporting TCAS RAs have been published in PANS-ATM, Document 4444. These documents provide international standardization for collision avoidance systems.

For the avionics, the Airlines Electronic Engineering Committee (AEEC) has published ARINC Characteristic 735A that defines the form, fit, and function of TCAS II units. The AEEC has also published ARINC Characteristic 718B for the Mode S transponder. Note that a Mode S transponder is required as part of a TCAS II installation.

Appendix E Airspace Description

As a key piece of the hazard analysis process, the group considered the different classes of airspace as individual system states. The likelihood determination for each hazard occurring in the different classes of airspace was based on the existing controls (ie level of ATC service provided in the airspace). Each control is specifically identified in column 5 of the PHAs (See Appendix F and Appendix G).



	Class A	Class B	Class C	Class D	Class E	Class G
Entry Requirements	ATC clearance	ATC clearance	Prior two-way communications	Prior two-way communications	Prior two-way communications*	Prior two-way communications*
Minimum Pilot Qualifications	Instrument Rating	Private or Student certification—local restrictions apply.	Student certificate	Student certificate	Student certificate	Student certificate
Two-Way Radio Communications	Yes	Yes	Yes	Yes	Yes, under IFR flight plan*	Yes*
Special VFR Allowed	No	Yes	Yes	Yes	Yes	N/A
VFR Visibility Minimum	N/A	3 statute miles	3 statute miles	3 statute miles	3 statute miles**	1 statute mile†
VFR Minimum Distance from Clouds	N/A	Clear of clouds	500' below, 1,000' above, 2,000' horizontal	500' below, 1,000' above, 2,000' horizontal	500' below,** 1,000' above, 2,000' horizontal	Clear of clouds†
VFR Aircraft Separation	N/A	All	IFR aircraft	Runway operations	None	None
Traffic Advisories	Yes	Yes	Yes	Workload permitting	Workload permitting	Workload permitting
Airport Application	N/A	• Radar • Instrument approaches • Weather • Control tower • High density	• Radar • Instrument approaches • Weather • Control tower	• Instrument approaches • Weather • Control tower	• Instrument approaches • Weather	• Control tower

*Exception: temporary tower or control tower present
**True only below 10,000 feet
†True only during day at or below 1,200 feet AGL (see 14 CFR part 91)

AGL—above ground level
FL—flight level
MSL—mean sea level

Figure 18 Airspace Classification chart

Appendix F Horizontal Maneuver PHA

F.1 Class A Airspace

Table 7 – PHA for Horizontal Maneuver / Class A airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk

1	Incorrect self-separation maneuver:
	• Roll Left
	  o Heading Chg
	• Roll Right
	  o Heading Chg
	• Roll to level
	• Level to level
	
	Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.
		• Pilot state estimate error of ownship
		• Pilot state and trajectory estimate errors of intruder
		• Incorrect display due to:
		a. TCAS errors:
		i. Position(dominated by bearing error)
		ii. Threat level
		iii. Vertical trend
		b. Intruder transponder failure
		c. Other equipment errors on ownship:
		i. Altitude
		ii. Airspeed
		iii. Heading
		iv. Flight plan
		• Pilot fails to detect display error
			Class A:
			• Complex traffic situations[1]
			• Performance difference between aircraft
			• High closure rates
			• Degrading environmental conditions (IMC)
				• Class A is controlled airspace[2]
				• All aircraft on IFR flight plan[3]
				• All aircraft transponder equipped (altitude encoding)[4,5]
				• All transponder altitude reports verified by ATC[6]
				• All aircraft receiving ATC separation services[7,8]
				• Manned aircraft prohibited from maneuvering on TCAS traffic display[9,10,11,12]
				• When TCAS equipped, manned aircraft pilots trained in the use of TCAS[13,14]
					• Loss of separation (Category A)[15]
					• Collision avoidance maneuver (ownship or intruder)
						Hazardous:
						
						Loss of separation at Category A constitutes a hazardous severity by definition. A collision avoidance maneuver may be required as a result of the loss of separation[16]
							Probable
							
							The fact that a horizontal maneuver would need to be initiated a significant distance in advance of CPA increases the probability of performing an incorrect maneuver.
							
							Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers
								High	**None**
									
									There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level.
									
									Inherent design deficiencies in the TCAS system position and intruder state measurements.
										High

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1 Draft Class A PHA (SRMD)
2 7110.65T, PCG C-6, CONTROLLED AIRSPACE c. 1.
3 91.135
4 91.135
5 Exceptions to transponder requirements are covered in 91.215
6 7110.65T Chapter 5, Section 2, 5-2-17
7 91.135
8 Aeronautical Information Manual, 3-2-2. b, 3-2.1. b, c
9 AC 20-151A Appendix A Section I Limitations (2)
10 AC 20-151A Appendix A Section III Procedures (1)
11 AC 120-55b 11.1.b.1….
12 Introduction to TCAS II Version 7, pp. 35
13 Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
14 AC 120-55b, 8.b. TCAS Training Program Requirements
15 7210.56
16 ATO SMS Version 2.1 pp39

F.1.1 System State and Controls

In Class A airspace, traffic situations can be complex. In addition, there may be significant differences among aircraft (and UA) performance characteristics. Many of the encounter geometries have high closure rates. The worst credible environmental conditions would be IMC (e.g. intruder aircraft would be unlikely to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class A airspace are numerous. All aircraft are flying an IFR flight plan. All aircraft are transponder equipped with altitude encoding, and transponder altitude reports are verified by ATC. All aircraft are under positive air traffic control and receiving ATC separation services. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.1.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class A airspace could lead to a Category A loss of separation and possibly require a collision avoidance maneuver by ownship UAS or by the intruder or both.

According to the SMS manual, a Category A loss of separation constitutes a hazardous severity.

Modeling and simulation[52] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class A Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

In general, the horizontal maneuver would need to be initiated a significant distance in advance of CPA (in the scenario described in section 3.1.3 - the maneuver would need to be started at a relative distance of 20 NM; or a time to CPA of 90 seconds).

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[52] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a loss of separation is probable. While all aircraft in Class A airspace are receiving ATC separation services, any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruder, is likely to degrade the level of safety and result in a loss of separation.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.1.3 Recommended Safety Requirements

Any aircraft in Class A airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class A airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Hazardous, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class A airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.2 Class B Airspace

Table 8 – PHA for Horizontal Maneuver / Class B airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class B:** • Complex traffic situations • High traffic levels (cluttered display) • Degrading environmental conditions (IMC) • High pilot/ATC workload	• All aircraft transponder equipped (altitude encoding)[1,2,3,4] • All transponder altitude reports verified by ATC[5] • All aircraft required to be equipped with two-way radio[6,7] • VFR aircraft must receive clearance before entering Class B[8] • All aircraft receiving ATC separation services [9] • Manned aircraft prohibited from maneuvering on TCAS traffic display[10,11,12,13] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[14,15]	• Loss of separation (Category A)[16] • Collision avoidance maneuver (ownship or intruder)	**Hazardous:** Loss of separation at Category A constitutes a hazardous severity by definition. A collision avoidance maneuver may be required as a result of the loss of separation[17]	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Complexity and density of system state leads to probable occurrence that a maneuver will result in a loss of separation	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] 91.131 (d)
[2] 7110.65T Chapter 7 Section 9, 7-9-1. a. 2.
[3] 7110.65T PCG C-6, CONTROLLED AIRSPACE, c.2.
[4] Exceptions to transponder requirements are covered in 91.215
[5] 7110.65T Chapter 5 Section 2, 5-2-17
[6] 91.131 (c), (2)
[7] 7110.65T Chapter 7 Section 9 7-9-1. a. 1.
[8] 7100.65T 7-9-2.a
[9] 7110.65T PCG, C-6, CONTROLLED AIRSPACE c. 2
[10] AC 20-151A Appendix A Section I Limitations (2)
[11] AC 20-151A Appendix A Section III Procedures (1)
[12] AC 120-55b 11.1.b.1….
[13] Introduction to TCAS II Nov 2000, pp. 35
[14] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[15] AC 120-55b, 8.b. TCAS Training Program Requirements
[16] 7210.56
[17] ATO SMS Version 2.1 pp39

F.2.1 System State and Controls

In Class B airspace, traffic situations can be complex. In addition, traffic levels can be high (cluttered display). Workloads for ATC and Pilots can be high. The worst credible environmental conditions would be IMC (e.g. intruder aircraft would be unlikely to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class B airspace are numerous. All aircraft are transponder equipped with altitude encoding, and transponder altitude reports are verified by ATC. All aircraft are required to be equipped with a two-way radio. All aircraft are receiving ATC separation services. VFR aircraft must receive clearance before entering Class B airspace. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.2.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class B airspace could lead to a Category A loss of separation and possibly require a collision avoidance maneuver by ownship UAS or by the intruder or both.

According to the SMS manual, a Category A loss of separation constitutes a hazardous severity.

Modeling and simulation[53] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class B Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

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[53] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a loss of separation is probable. While all aircraft in Class B airspace are receiving separation services, any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a loss of separation.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.2.3 Recommended Safety Requirements

Any aircraft in Class B airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class B airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Hazardous, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class B airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.3 Class C Airspace

Table 9 – PHA for Horizontal Maneuver / Class C airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class C:** • Complex traffic situations • Moderate traffic levels • Marginal VMC • Moderate pilot/ATC workload • High UAS pilot workload • ATC is not providing separation services between VFR aircraft[1]	• ATC is providing separation services for IFR aircraft[2] • ATC is providing separation services, traffic advisories and safety alerts between IFR and VFR aircraft[3] • Mandatory traffic advisories and safety alerts between VFR aircraft[4,5] • All aircraft are transponder equipped[6,7,8,9,10] • Traffic advisories are issued to aircraft (VFR or IFR) when in the controllers judgment, their proximity may diminish to less than the applicable separation minima[11] • All aircraft required to be equipped with two-way radio[12] • All aircraft are in radar coverage[13,14] • Communications with ATC are established and maintained[15,16] • Manned aircraft prohibited from maneuvering on TCAS traffic display[17,18,19,20] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[21,22]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[23] .	**Remote** In Class C airspace ATC keeps all aircraft separated; limiting the likelihood of mid air collision to below probable.	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

[1] 7110.65T Chapter 7 Section 8, 7.8.2. a.4.
[2] 7110.65T Chapter 7 Section 8 7-8-2 a. 2.
[3] 7110.65T Chapter 7 Section 8, 7-8-2. a.3.
[4] 7110.65T Chapter 2 Section 1, 2-1.21
[5] 7110.65T Chapter 7 Section 8, 7-8-2 a.4.
[6] 91.215 (b),(1)
[7] 91.130 (2), (d)
[8] Aeronautical Information Manual , Chapter 3, Section 2, 3-2-4 c. 2.
[9] Exceptions to transponder requirements are covered in 91.215
[10] 7110.65T Chapter 7, Section 8, 7-8-1
[11] 7110.65T Chapter 2 Section 1, 2-1-21
[12] 91.130
[13] Aeronautical Information Manual 3-2-4, a
[14] 7110.65T 7-8-2, e.
[15] 7110.65T C-6, 3
[16] 91.130, c.
[17] AC 20-151A Appendix A Section I Limitations (2)
[18] AC 20-151A Appendix A Section III Procedures (1)
[19] AC 120-55b 11.1.b.1….
[20] Introduction to TCAS II Nov 2000, pp. 35
[21] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[22] AC 120-55b, 8.b. TCAS Training Program Requirements
[23] ATO SMS Version 2.1 pp39

F.3.1 System State and Controls

In Class C airspace, traffic situations can be complex. Traffic levels can be moderate, with moderate workloads for ATC and Pilots. The UAS pilot's workload may be high. ATC will not be providing VFR traffic with separation services. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

Class C airspace provides some existing controls to all aircraft. ATC does provide mandatory traffic advisories and safety alerts between VFR aircraft. ATC provides separation services, traffic advisories and safety alerts between IFR and VFR aircraft. ATC is providing separation services for IFR aircraft. All aircraft must be equipped with a transponder, two-way radio and in communication with ATC. All aircraft are within radar coverage. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.3.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class C airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[54] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class C Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

[54] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a mid-air collision is remote. While all IFR aircraft in Class C airspace are receiving separation services, VFR aircraft are only receiving mandatory traffic advisories and safety alerts. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that has a remote probability of culminating in a mid-air collision.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.3.3 Recommended Safety Requirements

Any aircraft in Class C airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class C airspace would be safer when the UAS is relying on ATC separation services, mandatory traffic advisories, and safety alerts. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class C airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.4 Class D Airspace

Table 10 – PHA for Horizontal Maneuver / Class D airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class D:** • Moderate traffic levels • Marginal VFR • High pilot/ATC workload • No transponder required for operations in Class D airspace[1] • No separation services are provided to VFR aircraft[2,3] • ATC may not have radar or may have an uncertified radar display[4]	• ATC is providing separation services for IFR aircraft[5] • All aircraft required to be equipped with two-way radio[6,7,8] • Communications with ATC are established and maintained[9,10] • Traffic advisories and safety alerts between VFR aircraft[11,12,13] • Manned aircraft prohibited from maneuvering on TCAS traffic display[14,15,16,17] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[18,19]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[20] Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] 91.215
[2] 7110.65T Pilot/Controller Glossary PCG C-6 D.
[3] Aeronautical Information Manual 3-2-5, e.
[4] 7110.65T 3-1-9 a
[5] 7110.65T PCG C-6, CONTROLLED AIRSPACE, a, b
[6] 7110.65T PCG C-6, 4.
[7] 91.129, c
[8] Aeronautical Information Manual, 3-2-5, b. 2.
[9] 7110.65T PCG C-6, 4
[10] 91.129, c.
[11] 7110.65T Chapter 2 Section 1, 2-1-21. b
[12] 7110.65T PCG S-1 SAFETY ALERT
[13] Aeronautical Information Manual 5-5-7, b
[14] AC 20-151A Appendix A Section I Limitations (2)
[15] AC 20-151A Appendix A Section III Procedures (1)
[16] AC 120-55b 11.1.b.1….
[17] Introduction to TCAS II Nov 2000, pp. 35
[18] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[19] AC 120-55b, 8.b. TCAS Training Program Requirements
[20] ATO SMS Version 2.1 pp39

F.4.1 System State and Controls

In Class D airspace, traffic levels can be moderate, with high workloads for ATC and Pilots. While IFR aircraft are under ATC control, VFR aircraft are not receiving ATC separation services. Not all aircraft are required to be transponder equipped, ATC may not have radar coverage in all areas or radar may not be certified for aircraft separation (e.g. BRITE Scope). The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class D airspace are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. All aircraft receive traffic advisories and safety alerts issued by ATC. All aircraft are responsible for see and avoid. All aircraft must be equipped with two-way radio and must maintain communications with ATC. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.4.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class D airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[55] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class D Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

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[55] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a mid-air collision is probable. While all IFR aircraft in Class D airspace are receiving separation services, VFR aircraft are only receiving mandatory traffic advisories and safety alerts. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.4.3 Recommended Safety Requirements

Any aircraft in Class D airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class D airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class D airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.5 Class E Airspace above 10,000 ft MSL

Table 11 – PHA for Horizontal Maneuver / Class E airspace above 10,000 ft MSL

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class E above 10,000 ft MSL including the airspace above Class B, Mode C veil[1], and above Class C (outer ring)[2]:** • Moderate traffic levels may exist when in proximity to an airport • Pilot/ATC workload increases when flying adjacent to an airport • No separation services are provided to VFR aircraft[3] • All transponder altitude reports verified by ATC for IFR traffic • ATC may not have radar • Potential high closure rates above 10,000 MSL • Marginal VFR • As required in the judgment of the controller traffic advisories and safety alerts between VFR aircraft[4]	• ATC is providing separation services for IFR aircraft[5] • Some aircraft will have two-way communication capability[6,7] • All aircraft transponder equipped (altitude encoding)[8] • Manned aircraft prohibited from maneuvering on TCAS traffic display[9,10,11,12] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[13,14]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[15] Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] CFR 14 Part 91.215
[2] CFR 14 Part 91.215 (b), 4
[3] Aeronautical Information Manual, 3-2-6, f.
[4] 7110.65T Chapter 2 Section 1, 2-1-21
[5] 7110.65T PCG C-6 and C-7 CONTROLLED AIRSPACE, c. 5, and CONTROLLED [ICAO]
[6] 91.127
[7] Aeronautical Information Manual 3-2-6, b. 2.
[8] 91.215 (b) (5) (i)
[9] AC 20-151A Appendix A Section I Limitations (2)
[10] AC 20-151A Appendix A Section III Procedures (1)
[11] AC 120-55b 11.1.b.1….
[12] Introduction to TCAS II Nov 2000, pp. 35
[13] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[14] AC 120-55b, 8.b. TCAS Training Program Requirements
[15] ATO SMS Version 2.1 pp39

F.5.1 System State and Controls

In Class E airspace above 10,000 ft MSL, traffic levels can be moderate when in proximity to any airport. Pilot and ATC workloads may increase when in proximity to an airport. VFR aircraft are not receiving ATC separation services. While all aircraft are required to be transponder equipped, ATC may not have radar coverage in all areas, and VFR aircraft altitudes may not be verified. Many of the encounter geometries have high closure rates. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class E airspace above 10,000 ft MSL are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. All aircraft are responsible for see and avoid. All aircraft are transponder equipped with altitude encoding, and all IFR aircraft transponder altitude reports are verified by ATC. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.5.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class E airspace above 10,000 ft MSL could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[56] suggests synthetic RAs on the order of 10^{-2} per flight hour (in Class E Airspace); indicating that a pilot determined threat should occur at least this frequently. In contrast, this likelihood is ten times more probable than in Class A, B, C, or D airspaces. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

[56] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a mid-air collision is probable. Aircraft on an IFR flight plan in Class E airspace above 10,000 ft MSL are receiving ATC separation services from other IFR aircraft. All aircraft are required to see and avoid other traffic. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.5.3 Recommended Safety Requirements

Any aircraft in Class E airspace above 10,000 ft attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class E airspace above 10,000 ft would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class E airspace above 10,000 ft MSL are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level.
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display.

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.6 Class E Airspace below 10,000 ft MSL

Table 12 – PHA for Horizontal Maneuver / Class E airspace below 10,000 ft MSL

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class E below 10,000 ft MSL not including the airspace above Class B, Mode C veil[1], or above Class C (outer ring)[2]:** • Moderate traffic levels may exist when adjacent to an Airport • Pilot/ATC workload increases when flying adjacent an Airport • Greater concentration of non-transponder equipped aircraft[3,4] • No separation services are provided to VFR aircraft[5] • Some aircraft may not have two-way communications[6,7] • ATC may not be able to provide radar services and may not have certified radar display capability[8] • Marginal VFR • Mandatory traffic advisories and safety alerts between VFR aircraft[9]	• ATC is providing separation services for IFR aircraft[10] • When operating in the vicinity of a Class E airport, two way communications are required unless otherwise authorized by ATC[11] • Manned aircraft prohibited from maneuvering on TCAS traffic display[12,13,14,15] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[16,17]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[18] Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

[1] CFR 14 Part 91.215
[2] CFR 14 Part 91.215 (b), 4
[3] 91.127
[4] Aeronautical Information Manual, 3-2-6, b. 2.
[5] Aeronautical Information Manual, 3-2-6, f.
[6] 91.127
[7] Aeronautical Information Manual 3-2-6, b. 2.
[8] 7110.65T 3-1-9, a
[9] 7110.65T Chapter 2 Section 1, 2-1-21
[10] 7110.65T PCG C-7 CONTROLLED AIRSPACE, c. 5, and CONTROLLED [ICAO]
[11] 91.127
[12] AC 20-151A Appendix A Section I Limitations (2)
[13] AC 20-151A Appendix A Section III Procedures (1)
[14] AC 120-55b 11.1.b.1….
[15] Introduction to TCAS II Nov 2000, pp. 35
[16] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[17] AC 120-55b, 8.b. TCAS Training Program Requirements
[18] ATO SMS Version 2.1 pp39

F.6.1 System State and Controls

In Class E airspace below 10,000 ft MSL, traffic levels can be moderate when in proximity to any airport. Pilot and ATC workloads may increase when in proximity to an airport. VFR aircraft are not receiving ATC separation services. Not all aircraft are required to be transponder equipped. ATC may not have radar coverage in all areas. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class E airspace below 10,000 ft MSL are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. When operating in the vicinity of a Class E airport, two way communications are required unless otherwise authorized by ATC. All aircraft are responsible for see and avoid. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

F.6.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class E airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[57] suggests synthetic RAs on the order of 10^{-2} per flight hour (in Class E Airspace); indicating that a pilot determined threat should occur at least this frequently. In contrast, this likelihood is ten times more probable than in Class A, B, C, or D airspaces. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

[57] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a mid-air collision is probable. Aircraft on an IFR flight plan in Class E airspace below 10,000 ft MSL are receiving ATC separation services from other IFR aircraft. All aircraft are required to see and avoid other traffic. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a horizontal maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

F.6.3 Recommended Safety Requirements

Any aircraft in Class E airspace below 10,000 ft MSL attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class E airspace below 10,000 ft MSL would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class E airspace below 10,000 ft MSL are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

F.7 Class G Airspace

Table 13 – PHA for Horizontal Maneuver / Class G airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Roll Left o Heading Chg • Roll Right o Heading Chg • Roll to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class G:** • Moderate traffic levels may exist when operating in proximity to an Airport • No ATC separation services provided[1] • No specific equipage required[2,3]	• VFR minimums apply[4] • Manned aircraft prohibited from maneuvering on TCAS traffic display[5,6,7,8] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[9,10]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[11] Maneuver may result in collision with non-transponding aircraft not visible on TCAS Maneuver may result in collision with intruder aircraft which may be maneuvering on visually acquiring the UA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Both aircraft have an obligation to exercise "see and avoid"; only the manned aircraft is effectively seeing and avoiding - thereby increasing the probability of collision. Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

[1] Pilot Handbook of Aeronautical Knowledge Chapter 14, pp 14-3
[2] Instrument Flying Handbook C8-1 pp 3 figure 8-1 two way communications required only when temporary control tower or control tower present
[3] 91.126
[4] Aeronautical Information Manual 3-3-2
[5] AC 20-151A Appendix A Section I Limitations (2)
[6] AC 20-151A Appendix A Section III Procedures (1)
[7] AC 120-55b 11.1.b.1….
[8] Introduction to TCAS II Nov 2000, pp. 35
[9] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[10] AC 120-55b, 8.b. TCAS Training Program Requirements
[11] ATO SMS Version 2.1 pp39

F.7.1 System State and Controls

In Class G airspace, traffic levels can be moderate when in proximity to any airport. No specific equipage required. All aircraft are responsible to see and avoid other aircraft. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring airborne communications, landmarks and features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical, for example in the geometry above, only the controller knows that the intruding aircraft will be leveling off 1000 ft above the UAS.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class G airspace are minimal. Few aircraft are flying an IFR flight plan. Many aircraft will not be transponder equipped with altitude encoding.

F.7.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class G airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a mid-air collision is probable. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a horizontal maneuver for self separation is "High Risk" based on the decision criteria presented in section 2.6.

F.7.3 Recommended Safety Requirements

Any aircraft in Class G airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. An intruder is more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder's TCAS would be more effective in tracking and generating RA's when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a horizontal maneuver for self separation in Class G airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

Appendix G Vertical Maneuver PHA

G.1 Class A Airspace

Table 14 – PHA for Vertical Maneuver / Class A airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class A:** • Complex traffic situations[1] • Performance difference between aircraft • High closure rates • Degrading environmental conditions (IMC)	• Class A is controlled airspace[2] • All aircraft on IFR flight plan[3] • All aircraft transponder equipped (altitude encoding)[4,5] • All transponder altitude reports verified by ATC[6] • All aircraft receiving ATC separation services[7,8] • Manned aircraft prohibited from maneuvering on TCAS traffic display[9,10,11,12] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[13,14]	• Loss of separation (Category A)[15] • Collision avoidance maneuver (ownship or intruder)	**Hazardous:** Loss of separation at Category A constitutes a hazardous severity by definition. A collision avoidance maneuver may be required as a result of the loss of separation[16]	**Remote** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

1 FAA UAPO Draft Class A PHA (SRMD)
2 7110.65T, PCG C-6, CONTROLLED AIRSPACE c. 1.
3 91.135
4 91.135
5 Exceptions to transponder requirements are covered in 91.215
6 7110.65T Chapter 5, Section 2, 5-2-17
7 91.135
8 Aeronautical Information Manual, 3-2-2. b, 3-2.1. b, c
9 AC 20-151A Appendix A Section I Limitations (2)
10 AC 20-151A Appendix A Section III Procedures (1)
11 AC 120-55b 11.1.b.1….
12 Introduction to TCAS II Version 7, pp. 35
13 Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
14 AC 120-55b, 8.b. TCAS Training Program Requirements
15 7210.56
16 ATO SMS Version 2.1 pp39

G.1.1 System State and Controls

In Class A airspace, traffic situations can be complex. In addition, there may be significant differences among aircraft (and UA) performance characteristics. Many of the encounter geometries have high closure rates. The worst credible environmental conditions would be IMC (e.g. intruder aircraft would be unlikely to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class A airspace are numerous. All aircraft are flying an IFR flight plan. All aircraft are transponder equipped with altitude encoding, and transponder altitude reports are verified by ATC. All aircraft are under positive air traffic control and receiving ATC separation services. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.1.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class A airspace could lead to a Category A loss of separation and possibly require a collision avoidance maneuver by ownship UAS or by the intruder or both.

According to the SMS manual, a Category A loss of separation constitutes a hazardous severity.

Modeling and simulation[58] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class A Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

In general, the vertical maneuver would need to be initiated a fair distance in advance of CPA (in the scenario described in section 3.2.3 - the maneuver would need to be started at a relative distance of 14 NM; or a time to CPA of 60 seconds).

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[58] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a loss of separation is remote. While all aircraft in Class A airspace are receiving ATC separation services, any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruder, is likely to degrade the level of safety and has a remote possibility to result in a loss of separation.

The current initial risk of performing a vertical maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

G.1.3 Recommended Safety Requirements

Any aircraft in Class A airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class A airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Hazardous, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class A airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.2 Class B Airspace

Table 15 – PHA for Vertical Maneuver / Class B airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class B:** • Complex traffic situations • High traffic levels (cluttered display) • Degrading environmental conditions (IMC) • High pilot/ATC workload	• All aircraft transponder equipped (altitude encoding)[1,2,3,4] • All transponder altitude reports verified by ATC[5] • All aircraft required to be equipped with two-way radio[6,7] • VFR aircraft must receive clearance before entering Class B[8] • All aircraft receiving ATC separation services [9] • Manned aircraft prohibited from maneuvering on TCAS traffic display[10,11,12,13] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[14,15]	• Loss of separation (Category A)[16] • Collision avoidance maneuver (ownship or intruder)	**Hazardous:** Loss of separation at Category A constitutes a hazardous severity by definition. A collision avoidance maneuver may be required as a result of the loss of separation[17]	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Complexity and density of system state leads to probable occurrence that a maneuver will result in a loss of separation	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] 91.131 (d)
[2] 7110.65T Chapter 7 Section 9, 7-9-1. a. 2.
[3] 7110.65T PCG C-6, CONTROLLED AIRSPACE, c.2.
[4] Exceptions to transponder requirements are covered in 91.215
[5] 7110.65T Chapter 5 Section 2, 5-2-17
[6] 91.131 (c), (2)
[7] 7110.65T Chapter 7 Section 9 7-9-1. a. 1.
[8] 7100.65T 7-9-2.a
[9] 7110.65T PCG, C-6, CONTROLLED AIRSPACE c. 2
[10] AC 20-151A Appendix A Section I Limitations (2)
[11] AC 20-151A Appendix A Section III Procedures (1)
[12] AC 120-55b 11.1.b.1….
[13] Introduction to TCAS II Nov 2000, pp. 35
[14] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[15] AC 120-55b, 8.b. TCAS Training Program Requirements
[16] 7210.56
[17] ATO SMS Version 2.1 pp39

G.2.1 System State and Controls

In Class B airspace, traffic situations can be complex. In addition, traffic levels can be high (cluttered display). Workloads for ATC and Pilots can be high. The worst credible environmental conditions would be IMC (e.g. intruder aircraft would be unlikely to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class B airspace are numerous. All aircraft are transponder equipped with altitude encoding, and transponder altitude reports are verified by ATC. All aircraft are required to be equipped with a two-way radio. All aircraft are receiving ATC separation services. VFR aircraft must receive clearance before entering Class B airspace. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.2.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class B airspace could lead to a Category A loss of separation and possibly require a collision avoidance maneuver by ownship UAS or by the intruder or both.

According to the SMS manual, a Category A loss of separation constitutes a hazardous severity.

Modeling and simulation[59] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class B Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

[59] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a loss of separation is probable. While all aircraft in Class B airspace are receiving separation services, any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is likely to culminate in a loss of separation.

The current initial risk of performing a vertical maneuver for self separation is "High Risk" based on the decision criteria presented in section 2.6.

G.2.3 Recommended Safety Requirements

Any aircraft in Class B airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class B airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder's TCAS would be more effective in tracking and generating RA's when the UA is not maneuvering.

The initial severity is Hazardous, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class B airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.3 Class C Airspace

Table 16 – PHA for Vertical Maneuver / Class C airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class C:** • Complex traffic situations • Moderate traffic levels • Marginal VMC • Moderate pilot/ATC workload • High UAS pilot workload • ATC is not providing separation services between VFR aircraft[1]	• ATC is providing separation services for IFR aircraft[2] • ATC is providing separation services, traffic advisories and safety alerts between IFR and VFR aircraft[3] • Mandatory traffic advisories and safety alerts between VFR aircraft[4,5] • All aircraft are transponder equipped[6,7,8,9,10] • Traffic advisories are issued to aircraft (VFR or IFR) when in the controllers judgment, their proximity may diminish to less than the applicable separation minima[11] • All aircraft required to be equipped with two-way radio[12] • All aircraft are in radar coverage[13,14] • Communications with ATC are established and maintained[15,16] • Manned aircraft prohibited from maneuvering on TCAS traffic display[17,18,19,20] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[21,22]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[23]	**Remote** In Class C airspace ATC keeps all aircraft separated; limiting the likelihood of mid air collision to below probable.	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] 7110.65T Chapter 7 Section 8, 7.8.2. a.4.
[2] 7110.65T Chapter 7 Section 8 7-8-2 a. 2.
[3] 7110.65T Chapter 7 Section 8, 7-8-2. a.3.
[4] 7110.65T Chapter 2 Section 1, 2-1.21
[5] 7110.65T Chapter 7 Section 8, 7-8-2 a.4.
[6] 91.215 (b),(1)
[7] 91.130 (2), (d)
[8] Aeronautical Information Manual , Chapter 3, Section 2, 3-2-4 c. 2.
[9] Exceptions to transponder requirements are covered in 91.215
[10] 7110.65T Chapter 7, Section 8, 7-8-1
[11] 7110.65T Chapter 2 Section 1, 2-1-21
[12] 91.130
[13] Aeronautical Information Manual 3-2-4, a
[14] 7110.65T 7-8-2, e.
[15] 7110.65T C-6, 3
[16] 91.130, c.
[17] AC 20-151A Appendix A Section I Limitations (2)
[18] AC 20-151A Appendix A Section III Procedures (1)
[19] AC 120-55b 11.1.b.1….
[20] Introduction to TCAS II Nov 2000, pp. 35
[21] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[22] AC 120-55b, 8.b. TCAS Training Program Requirements
[23] ATO SMS Version 2.1 pp39

G.3.1 System State and Controls

In Class C airspace, traffic situations can be complex. Traffic levels can be moderate, with moderate workloads for ATC and Pilots. The UAS pilot's workload may be high. ATC will not be providing VFR traffic with separation services. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

Class C airspace provides some existing controls to all aircraft. ATC does provide mandatory traffic advisories and safety alerts between VFR aircraft. ATC provides separation services, traffic advisories and safety alerts between IFR and VFR aircraft. ATC is providing separation services for IFR aircraft. All aircraft must be equipped with a transponder, two-way radio and in communication with ATC. All aircraft are within radar coverage. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.3.2 Possible Outcome

The worst credible effect of making a horizontal maneuver for self separation in Class C airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[60] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class C Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

[60] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a mid-air collision is remote. While all IFR aircraft in Class C airspace are receiving separation services, VFR aircraft are only receiving mandatory traffic advisories and safety alerts. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that has a remote probability of culminating in a mid-air collision.

The current initial risk of performing a vertical maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

G.3.3 Recommended Safety Requirements

Any aircraft in Class C airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class C airspace would be safer when the UAS is relying on ATC separation services, mandatory traffic advisories, and safety alerts. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class C airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.4 Class D Airspace

Table 17 – PHA for Vertical Maneuver / Class D airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk

1	Incorrect self-separation maneuver:
	• Climb
	  o Rate
	• Descent
	  o Rate
	• Rate to level
	• Level to level
	
	Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.
		• Pilot state estimate error of ownship
		• Pilot state and trajectory estimate errors of intruder
		• Incorrect display due to:
		a. TCAS errors:
		i. Position(dominated by bearing error)
		ii. Threat level
		iii. Vertical trend
		b. Intruder transponder failure
		c. Other equipment errors on ownship:
		i. Altitude
		ii. Airspeed
		iii. Heading
		iv. Flight plan
		• Pilot fails to detect display error
			Class D:
			• Moderate traffic levels
			• Marginal VFR
			• High pilot/ATC workload
			• No transponder required for operations in Class D airspace[1]
			• No separation services are provided to VFR aircraft[2,3]
			• ATC may not have radar or may have an uncertified radar display[4]
				• ATC is providing separation services for IFR aircraft[5]
				• All aircraft required to be equipped with two-way radio[6,7,8]
				• Communications with ATC are established and maintained[9,10]
				• Traffic advisories and safety alerts between VFR aircraft[11,12,13]
				• Manned aircraft prohibited from maneuvering on TCAS traffic display[14,15,16,17]
				• When TCAS equipped, manned aircraft pilots trained in the use of TCAS[18,19]
					• Mid-air collision	**Catastrophic:**
						
						Mid-air collision by definition is considered catastrophic[20]
						
						Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA
							Probable
							
							Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers
								High	**None**
									
									There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level.
									
									Inherent design deficiencies in the TCAS system position and intruder state measurements.
										High

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[1] 91.215
[2] 7110.65T Pilot/Controller Glossary PCG C-6 D.
[3] Aeronautical Information Manual 3-2-5, e.
[4] 7110.65T 3-1-9 a
[5] 7110.65T PCG C-6, CONTROLLED AIRSPACE, a, b
[6] 7110.65T PCG C-6, 4.
[7] 91.129, c
[8] Aeronautical Information Manual, 3-2-5, b. 2.
[9] 7110.65T PCG C-6, 4
[10] 91.129, c.
[11] 7110.65T Chapter 2 Section 1, 2-1-21. b
[12] 7110.65T PCG S-1 SAFETY ALERT
[13] Aeronautical Information Manual 5-5-7, b
[14] AC 20-151A Appendix A Section I Limitations (2)
[15] AC 20-151A Appendix A Section III Procedures (1)
[16] AC 120-55b 11.1.b.1….
[17] Introduction to TCAS II Nov 2000, pp. 35
[18] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[19] AC 120-55b, 8.b. TCAS Training Program Requirements
[20] ATO SMS Version 2.1 pp39

G.4.1 System State and Controls

In Class D airspace, traffic levels can be moderate, with high workloads for ATC and Pilots. While IFR aircraft are under ATC control, VFR aircraft are not receiving ATC separation services. Not all aircraft are required to be transponder equipped, ATC may not have radar coverage in all areas or radar may not be certified for aircraft separation (BRITE Scope). The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class D airspace are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. All aircraft receive traffic advisories and safety alerts issued by ATC. All aircraft are responsible for see and avoid. All aircraft must be equipped with two-way radio and must maintain communications with ATC. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.4.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class D airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[61] suggests synthetic RAs on the order of 10^{-3} per flight hour (in Class D Airspace); indicating that a pilot determined threat should occur at least this frequently. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

[61] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a mid-air collision is probable. While all IFR aircraft in Class D airspace are receiving separation services, VFR aircraft are only receiving mandatory traffic advisories and safety alerts. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a vertical maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

G.4.3 Recommended Safety Requirements

Any aircraft in Class D airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class D airspace would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class D airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.5 Class E Airspace above 10,000 ft MSL

Table 18 – PHA for Vertical Maneuver / Class E airspace above 10,000 ft MSL

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class E above 10,000 ft MSL including the airspace above Class B, Mode C veil[1], and above Class C (outer ring)[2]:** • Moderate traffic levels may exist when in proximity to an Airport • Pilot/ATC workload increases when flying adjacent to an Airport • No separation services are provided to VFR aircraft[3] • All transponder altitude reports verified by ATC for IFR traffic • ATC may not have radar • Potential high closure rates above 10,000 MSL • Marginal VFR • As required in the judgment of the controller traffic advisories and safety alerts between VFR aircraft[4]	• ATC is providing separation services for IFR aircraft[5] • Some aircraft will have two-way communication capability[6,7] • All aircraft transponder equipped (altitude encoding)[8] • Manned aircraft prohibited from maneuvering on TCAS traffic display[9,10,11,12] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[13,14]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[15] Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] CFR 14 Part 91.215
[2] CFR 14 Part 91.215 (b), 4
[3] Aeronautical Information Manual, 3-2-6, f.
[4] 7110.65T Chapter 2 Section 1, 2-1-21
[5] 7110.65T PCG C-6 and C-7 CONTROLLED AIRSPACE, c. 5, and CONTROLLED [ICAO]
[6] 91.127
[7] Aeronautical Information Manual 3-2-6, b. 2.
[8] 91.215 (b) (5) (i)
[9] AC 20-151A Appendix A Section I Limitations (2)
[10] AC 20-151A Appendix A Section III Procedures (1)
[11] AC 120-55b 11.1.b.1….
[12] Introduction to TCAS II Nov 2000, pp. 35
[13] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[14] AC 120-55b, 8.b. TCAS Training Program Requirements
[15] ATO SMS Version 2.1 pp39

G.5.1 System State and Controls

In Class E airspace above 10,000 ft MSL, traffic situations can moderate when in proximity to any airport. Pilot and ATC workloads may increase when in proximity to an airport. VFR aircraft are not receiving ATC separation services. While all aircraft are required to be transponder equipped, ATC may not have radar coverage in all areas, and VFR aircraft altitudes may not be verified. Many of the encounter geometries have high closure rates. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class E airspace above 10,000 feet MSL are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. All aircraft are responsible for see and avoid. All aircraft are transponder equipped with altitude encoding, and all IFR aircraft transponder altitude reports are verified by ATC. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.5.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class E airspace above 10,000 ft MSL could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[62] suggests synthetic RAs on the order of 10^{-2} per flight hour (in Class E Airspace); indicating that a pilot determined threat should occur at least this frequently. In contrast, this likelihood is ten times more probable than in Class A, B, C, or D airspaces. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

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[62] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a mid-air collision is probable. Aircraft on an IFR flight plan in Class E airspace above 10,000 ft MSL and are receiving ATC separation services from other IFR aircraft. All aircraft are required to see and avoid other traffic. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is probable to culminate in a mid-air collision.

The current initial risk of performing a vertical maneuver for self separation is "High Risk" based on the decision criteria presented in section 2.6.

G.5.3 Recommended Safety Requirements

Any aircraft in Class E airspace above 10,000 ft attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class E airspace above 10,000 ft would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder's TCAS would be more effective in tracking and generating RA's when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class E airspace above 10,000 ft MSL are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.6 Class E Airspace below 10,000 ft MSL

Table 19 – PHA for Vertical Maneuver / Class E airspace below 10,000 ft MSL

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class E below 10,000 ft MSL not including the airspace above Class B, Mode C veil[1], or above Class C (outer ring)[2]:** • Moderate traffic levels may exist when adjacent to an Airport • Pilot/ATC workload increases when flying adjacent an Airport • Greater concentration of non-transponder equipped aircraft[3,4] • No separation services are provided to VFR aircraft[5] • Some aircraft may not have two-way communications[6,7] • ATC may not be able to provide radar services and may not have certified radar display capability[8] • Marginal VFR • Mandatory traffic advisories and safety alerts between VFR aircraft[9]	• ATC is providing separation services for IFR aircraft[10] • When operating in the vicinity of a Class E airport, two way communications are required unless otherwise authorized by ATC[11,12] • Manned aircraft prohibited from maneuvering on TCAS traffic display[13,14,15,16] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[17,18]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[19] Maneuver may result in collision with intruder aircraft which may be maneuvering on intruder generated RA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] CFR 14 Part 91.215
[2] CFR 14 Part 91.215 (b), 4
[3] 91.127
[4] Aeronautical Information Manual, 3-2-6, b. 2.
[5] Aeronautical Information Manual, 3-2-6, f.
[6] 91.127
[7] Aeronautical Information Manual 3-2-6, b. 2.
[8] 7110.65T 3-1-9, a
[9] 7110.65T Chapter 2 Section 1, 2-1-21
[10] 7110.65T PCG C-7 CONTROLLED AIRSPACE, c. 5, and CONTROLLED [ICAO]
[11] 91.127
[12] Aeronautical Information Manual 3-2-6, b. 2.
[13] AC 20-151A Appendix A Section I Limitations (2)
[14] AC 20-151A Appendix A Section III Procedures (1)
[15] AC 120-55b 11.1.b.1….
[16] Introduction to TCAS II Nov 2000, pp. 35
[17] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[18] AC 120-55b, 8.b. TCAS Training Program Requirements
[19] ATO SMS Version 2.1 pp39

G.6.1 System State and Controls

In Class E airspace below 10,000 ft MSL, traffic levels can be moderate when in proximity to any airport. Pilot and ATC workloads may increase when in proximity to an airport. VFR aircraft are not receiving ATC separation services. Not all aircraft are required to be transponder equipped. ATC may not have radar coverage in all areas. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring recent ATC communications between the intruder aircraft and ATC, fixes or waypoints, SID/STARS, features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class E airspace below 10,000 ft MSL are limited. Only aircraft on an IFR flight plan are receiving ATC separation services from other IFR aircraft. When operating in the vicinity of a Class E airport, two way communications are required unless otherwise authorized by ATC. All aircraft are responsible for see and avoid. When TCAS equipped, all manned aircraft pilots are trained on the use of TCAS, and are prohibited from maneuvering on TCAS traffic display.

G.6.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class E airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

Modeling and simulation[63] suggests synthetic RAs on the order of 10^{-2} per flight hour (in Class E Airspace); indicating that a pilot determined threat should occur at least this frequently. In contrast, this likelihood is ten times more probable than in Class A, B, C, or D airspaces. It is plausible that pilots would perform self-separation maneuvers more frequently and at the larger self-separation distances.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

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[63] Kochenderfer, Correlated Encounter Model for cooperative aircraft in the NAS

The likelihood that the hazard will result in a mid-air collision is probable. Aircraft on an IFR flight plan in Class E airspace below 10,000 ft MSL are receiving ATC separation services from other IFR aircraft. All aircraft are required to see and avoid other traffic. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is likely to culminate in a mid-air collision.

The current initial risk of performing a vertical maneuver for self separation is “High Risk” based on the decision criteria presented in section 2.6.

G.6.3 Recommended Safety Requirements

Any aircraft in Class E airspace below 10,000 ft MSL attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. The analysis indicates that all aircraft in Class E airspace below 10,000 ft MSL would be safer when the UAS is relying on ATC separation services. An intruder is also more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder’s TCAS would be more effective in tracking and generating RA’s when the UA is not maneuvering.

The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class E airspace below 10,000 ft MSL are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.

G.7 Class G Airspace

Table 20 – PHA for Vertical Maneuver / Class G airspace

(1) Hazard #	(2) Hazard Description	(3) Causes	(4) System State	(5) Existing Control or Requirement	(6) Possible Effects	(7) Severity/ Rationale	(8) Likelihood/ Rationale	(9) Current/ Initial Risk	(10) Recommended Safety Requirements	(11) Predicted Residual Risk
1	Incorrect self-separation maneuver: • Climb o Rate • Descent o Rate • Rate to level • Level to level Note: Pilot maneuvering on presence of other traffic for the intended function of providing self-separation from other traffic.	• Pilot state estimate error of ownship • Pilot state and trajectory estimate errors of intruder • Incorrect display due to: a. TCAS errors: i. Position(dominated by bearing error) ii. Threat level iii. Vertical trend b. Intruder transponder failure c. Other equipment errors on ownship: i. Altitude ii. Airspeed iii. Heading iv. Flight plan • Pilot fails to detect display error	**Class G:** • Moderate traffic levels may exist when operating in proximity to an Airport • No ATC separation services provided[1] • No specific equipage required[2,3]	• VFR minimums apply[4] • Manned aircraft prohibited from maneuvering on TCAS traffic display[5,6,7,8] • When TCAS equipped, manned aircraft pilots trained in the use of TCAS[9,10]	• Mid-air collision	**Catastrophic:** Mid-air collision by definition is considered catastrophic[11] Maneuver may result in collision with non-transponding aircraft not visible on TCAS Maneuver may result in collision with intruder aircraft which may be maneuvering on visually acquiring the UA	**Probable** Compelling display of traffic information coupled with procedures allowing maneuvers on same likely to induce incorrect maneuvers Both aircraft have an obligation to exercise “see and avoid”; only the manned aircraft is effectively seeing and avoiding - thereby increasing the probability of collision. Presence of VFR increases the occurrence of unknown intent and unknown behavior	**High**	**None** There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level. Inherent design deficiencies in the TCAS system position and intruder state measurements.	**High**

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[1] Pilot Handbook of Aeronautical Knowledge Chapter 14, pp 14-3
[2] Instrument Flying Handbook C8-1 pp 3 figure 8-1 two way communications required only when temporary control tower or control tower present
[3] 91.126
[4] Aeronautical Information Manual 3-3-2
[5] AC 20-151A Appendix A Section I Limitations (2)
[6] AC 20-151A Appendix A Section III Procedures (1)
[7] AC 120-55b 11.1.b.1….
[8] Introduction to TCAS II Nov 2000, pp. 35
[9] Except for Part 121 operations, there is no standard level of training in the use of TCAS. The use of installed TCAS II must be included in the aircraft AOM/POH
[10] AC 120-55b, 8.b. TCAS Training Program Requirements
[11] ATO SMS Version 2.1 pp39

G.7.1 System State and Controls

In Class G airspace, traffic levels can moderate when in proximity to any airport. No specific equipage required. All aircraft are responsible to see and avoid other aircraft. The worst credible environmental conditions would be marginal VMC (e.g. intruder aircraft may or may-not be able to see and avoid the UA).

It is clear that a pilot depending solely on the TCAS display does not have reliable information about an intruder's "intent". At best, the pilot would have to assess the intruder's intent from monitoring airborne communications, landmarks and features present on aeronautical charts, or from personal experience. In the worst credible circumstances, not knowing the intruder's intent can be critical.

The lack of intruder vertical rate information, display of vertical rate is limited to only vertical trend indicator arrow (>=500 FPM), and the limited resolution in vertical separation distance (100 ft altitude quantization), limits the ability to accurately project vertical separation from intruder at CPA by observing quantized altitude changes.

Inaccuracies in TCAS bearing resolution prevent the precise placement of intruding traffic on the display. In addition, when the UAS is actively turning, the TCAS display will lag "truth" (as a result of tracker lag).

The existing controls in Class G airspace are minimal. Few aircraft are flying an IFR flight plan. Many aircraft will not be transponder equipped with altitude encoding.

G.7.2 Possible Outcome

The worst credible effect of making a vertical maneuver for self separation in Class G airspace could lead to a mid-air collision.

According to the SMS manual, a mid-air collision risk constitutes a catastrophic severity.

A compelling display of traffic information coupled with the inaccurate and potentially incomplete information on the TCAS display, with procedures allowing maneuvers, is likely to induce an unsafe maneuver.

The likelihood that the hazard will result in a mid-air collision is probable. Any aircraft maneuvering without maintaining an accurate track (equivalent to maintaining visual contact) on the intruding aircraft is likely to begin a chain of events that is likely to culminate in a mid-air collision.

The current initial risk of performing a vertical maneuver for self separation is "High Risk" based on the decision criteria presented in section 2.6.

G.7.3 Recommended Safety Requirements

Any aircraft in Class G airspace attempting to maneuver based solely on the TCAS display for the purpose of self separating would likely induce more confusion and risk. An intruder is more likely to effectively see and avoid the UA if the UA is not maneuvering. Similarly, an intruder's TCAS would be more effective in tracking and generating RA's when the UA is not maneuvering.

TCAS on UAS v 1.0 (March 21, 2011)
The initial severity is Catastrophic, and our decision criteria (section 2.6) discourages use of procedural mitigations strategies for Catastrophic and Hazardous outcomes. The recommended safety requirements for performing a vertical maneuver for self separation in Class G airspace are as follows:

- There are no credible mitigation strategies that can be implemented to reduce the risk to an acceptable level
- Inherent design deficiencies in the TCAS system position and intruder state measurements limit the fidelity of the TCAS display

The predicted residual risk remains High. Therefore, maneuvering based solely on the TCAS display should not be allowed in this airspace.