SC-228 Defining the Collision Avoidance Region for DAA Systems

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Abstract

Unmanned aircraft systems (UAS) will be required to equip with a detect-and-avoid (DAA) system in order to satisfy the federal aviation regulations to maintain well clear of other aircraft, some of which may be equipped with a Traffic Collision Avoidance System (TCAS) to mitigate the possibility of mid-air collisions. As such, the minimum operational performance standards (MOPS) for UAS DAA systems are being designed with TCAS interoperability in mind by a group of industry, government, and academic institutions named RTCA Special Committee-228 (SC-228). This document will discuss the development of the spatial-temporal volume known as the collision avoidance region in which the DAA system is not allowed to provide vertical guidance to maintain or regain DAA well clear that could conflict with resolution advisories (RAs) issued by the intruder aircraft's TCAS system.

Three collision avoidance region definition candidates were developed based on the existing TCAS RA and DAA alerting definitions. They were evaluated against each other in terms of their interoperability with TCAS RAs and DAA alerts in an unmitigated factorial encounter analysis of 1.3 million simulated pairs. Based on the results of the analysis, the collision avoidance region definition for DAA systems below was recommended to and accepted by RTCA SC-228:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$
with
$$\tau^*_{\text{mod}} = 50 \text{ seconds}, \; DMOD = 1.1 \text{ NM}, \; \tau^*_v = 50 \text{ seconds, and } h^* = 800 \text{ ft}$$
("OR-h")

Overview

This paper describes in detail how this recommendation for the definition of the collision avoidance region was made. The next section presents the three collision avoidance region definition candidates that were evaluated and the underlying reasons for testing them. Following that is a description of the TCAS system and the DAA Warning alert definition that were used to evaluate the interoperability of each collision avoidance region definition candidate. The section after that specifies the test parameters that were used to simulate the 1.3 million encounters analyzed in this study. The encounter set is intended to capture the range of encounter angles and closure rates that could occur in the airspace. The interoperability of the three collision avoidance region definition candidates with regard to TCAS RAs and DAA Warning alerts are then analyzed in terms of when the collision avoidance region threshold is crossed (if ever) relative to when DAA Warning alerts and TCAS RAs are issued (if ever). Lastly, the findings of the research are summarized.

Collision Avoidance Region Definitions

To prevent the ownship aircraft's DAA system from providing vertical guidance to maintain or regain DAA well clear that could conflict with RAs issued by the intruder aircraft's TCAS system, the collision avoidance region should be large enough to encompass all geometries that would trigger a TCAS RA (i.e., the TCAS RA region). However, the collision avoidance region should also be small enough to avoid limiting DAA vertical guidance when the ownship and intruder aircraft are outside of the TCAS RA region at initial DAA Warning alert.

Three collision avoidance region definition candidates were developed to achieve these dual objectives:

1. The "AND" definition, which has a form like the DAA alerting definition that connects all of the conditions by "AND" operators but does not encompass the TCAS RA region because the two vertical conditions are connected by an "AND" operator instead of an "OR" operator (verified by TCAS experts at MIT-Lincoln Laboratories and the MITRE Corporation):

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ AND } ZTHR < ZTHR^*)$$
$$\text{with} \qquad \text{("AND")}$$
$$\tau^*_{\text{mod}} = 50 \text{ sec}, \; DMOD = 1.1 \text{ NM}, \; \tau^*_v = 50 \text{ sec, and } ZTHR^* = 800 \text{ ft}$$

2. The "OR" definition that connects the two vertical conditions by an "OR" operator instead of an "AND" operator in order to encompass the TCAS RA region but still uses a "vertical separation at CPA" condition instead of a "current vertical separation" condition as in the DAA alerting definition:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } ZTHR < ZTHR^*)$$
$$\text{with} \qquad \text{("OR")}$$
$$\tau^*_{\text{mod}} = 50 \text{ sec}, \; DMOD = 1.1 \text{ NM}, \; \tau^*_v = 50 \text{ sec, and } ZTHR^* = 800 \text{ ft}$$

3. The "OR-h" definition that also encompasses the TCAS RA region like the "OR" definition except using a "current vertical separation" condition as in the DAA alerting definition instead of a "vertical separation at CPA" condition:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$
$$\text{with} \qquad \text{("OR-h")}$$
$$\tau^*_{\text{mod}} = 50 \text{ seconds}, \; DMOD = 1.1 \text{ NM}, \; \tau^*_v = 50 \text{ seconds, and } h^* = 800 \text{ ft}$$

The parameter threshold values were chosen because they are the largest values used by TCAS II with an additional 15 seconds to account for both pilot response and TCAS II altitude tracker response.

TCAS

This study used TCAS II version 7.1 software tailored with a convenient interface to integrate into different testing platforms. It computes Proximate Traffic messages, traffic advisories (TAs), and resolution advisories (RAs). This study focuses specifically on TCAS RAs, especially with regard to when they are issued relative to when the collision avoidance region is crossed (if ever). Neither the ownship nor the intruder aircraft ever maneuver in this unmitigated simulation study, though.

DAA Warning Alert Definition

The DAA Warning alert definition in this study uses the same types of parameters and has the same form as the well clear definition. A buffer of about 0.09 NM was added to the well clear DMOD and HMD* thresholds of 4000 ft to model what a DAA system might use to guard against the effects of uncertainty. The modified tau and current vertical separation thresholds are the same as in the well clear definition.

In this study, a DAA Warning alert is issued if the following is predicted to happen within the next 40 seconds, which is the minimum average time of alert for the Hazard Zone of Warning alerts in the MOPS plus a buffer of 10 seconds:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } HMD < HMD^* \text{ AND } h < h^*$$
$$\text{with} \qquad \text{(DAA Warning)}$$
$$\tau^*_{\text{mod}} = 35 \text{ sec}, DMOD = 0.75 \text{ NM}, HMD^* = 0.75 \text{ NM, and } h^* = 450 \text{ ft}$$

Experiment Setup

The three collision avoidance region definition candidates were evaluated using 1.3 million unmitigated encounters simulated using all combinations of the parameters in Table 1 to capture the range of encounter angles and closure rates that could occur in the NAS. Note that this approach includes the rare “corner cases” that do not frequently occur in the NAS due to the expected nature and location of UAS missions and VFR flight trajectories. In addition, all encounters were simulated without uncertainty to ensure that the sequences of DAA Warning alerts, collision avoidance region crossings, and TCAS RAs are entirely determined by the encounter geometries.

Table 1 Test parameters

Parameter	# Values	Values
Ownship ground speed	4	50, 100, 150, 200 kts
Ownship heading	1	0 deg
Ownship vertical speed	1	0 ft/min
Intruder ground speed	5	50, 100, 150, 200, 250 kts
Intruder heading	12	0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 deg
Intruder vertical speed	9	-2000, -1500, -1000, -500, 0, 500, 1000, 1500, 2000 ft/min
Horizontal intruder trajectory shift	9	0 nmi: (x, y) = (0, 0) 0.5 nmi: (x, y) = (0.5, 0), (-0.5, 0), (0, 0.5), (0, -0.5) 1.5 nmi: (x, y) = (1.5, 0), (-1.5, 0), (0, 1.5), (0, -1.5)
Vertical intruder trajectory shift	7	-1000, -500, -250, 0, 250, 500, 1000 ft
Ownship trial plan maneuver turn rate	2	1.5, 3 deg/sec
Ownship trial plan climb/descent rate	5	(500, 500), (1000, 1000), (2000, 2000), (2000, 1000), (1000, 2000) ft/min

In each encounter, the ownship aircraft was simulated flying level at altitude 5000 ft heading north. The ownship ground speeds ranged between 50 and 200 kts to span the expected performance range of UAS aircraft. To cover the range of possible encounter situations, intruders flying level as well as intruders climbing and descending at vertical speeds up to 2000 ft/min were simulated. In addition, intruders flying at speeds between 50 and 250 kts in encounters at a wide range of angles relative to the ownship aircraft from the front, behind, and sides were also simulated. Furthermore, encounters with CPA from 0 NMI horizontally and 0 ft vertically up through 1.5 NMI horizontally and 1000 ft vertically were also simulated. Last but not least, guidance information for the ownship aircraft using different turn rates and climb and descent values were also collected.

Interoperability Metrics

This study evaluates the interoperability of the three collision avoidance region definition candidates with regard to DAA Warning alerts and TCAS RAs. More specifically, it analyzes when collision avoidance region thresholds are crossed (if ever) relative to when DAA Warning alerts and TCAS RAs are issued (if ever).

Note that the interoperability of the collision avoidance region with the TCAS RA region is more important because this is when the ownship and intruder aircraft are in closer proximity and the encounter is in a more safety-critical state. It is crucial that the collision avoidance region threshold is crossed before TCAS RA is issued in order for the DAA system to suppress vertical guidance that could conflict with RAs issued by the intruder aircraft's TCAS system. In other words, TCAS RAs ideally would never occur before collision avoidance region threshold crossing, and there should never be any cases in which a TCAS RA is issued but collision avoidance region threshold crossing never occurs.

The following is a list of undesirable situations and desirable situations that will be analyzed:

Undesirable situations (fewer is preferable):

1. TCAS RA before collision avoidance region crossing
2. TCAS RA without collision avoidance region crossing
3. Collision avoidance region crossing without TCAS RA
4. Collision avoidance region crossing before DAA Warning alert
5. Collision avoidance region crossing without DAA Warning alert

Desirable situations (more is preferable):

1. Collision avoidance region crossing before TCAS RA
2. DAA Warning before collision avoidance region crossing

The three collision avoidance region definition candidates are evaluated with regard to how often these situations occur. More specifically, percentages are calculated for each situation where the numerator is the number of encounters with each respective situation. The denominators used in these calculations are listed in Table 2.

Table 2 Denominators of the interoperability metrics

Situation Type	Situation #	"AND"	"OR"	"OR-h"
Undesirable	1	343,100	343,100	343,100
Undesirable	2	343,100	343,100	343,100
Undesirable	3	829,380	1,113,180	1,194,080
Undesirable	4	829,380	1,113,180	1,194,080
Undesirable	5	829,380	1,113,180	1,194,080
Desirable	1	829,380	1,113,180	1,194,080
Desirable	2	719,280	719,280	719,280

The denominator for the first two undesirable situations is the number of encounters with TCAS RA, which was 343,100 across all analyses.

The denominator for the last three undesirable situations and the first desirable situation is the number of encounters in which the collision avoidance region threshold was crossed. As expected, it is dependent on which of the three collision avoidance region definition candidates is used. There were 829,380 cases when the "AND" definition was used, 1,113,180 cases when the "OR" definition was used, and 1,194,080 cases when the "OR-h" definition was used.

The denominator for the last desirable situation is the number of DAA Warning alerts, which was 719,280 across all analyses.

Results

When comparing the three collision avoidance region definitions, the primary metrics are: 1) the percentage of TCAS RAs that occur before collision avoidance region crossing, and 2) the percentage of TCAS RAs that occur without collision avoidance region crossing. This is because these are safety-critical situations in which incompatible guidance can create a safety hazard. More specifically, it is most important to ensure that the ownship aircraft's DAA system does not provide vertical guidance that could conflict with RAs issued by the intruder aircraft's TCAS system in these safety-critical situations when the two aircraft are in close proximity.

Results Against "AND" Collision Avoidance Region Definition

Table 3 shows the prevalence of encounter situations with undesirable events for each of the three collision avoidance region definition candidates. The most important difference between them is that the "AND" definition is the only one that has the highly undesirable cases where TCAS RA either occurs before or without collision avoidance region crossing, but the "OR" and "OR-h" definitions do not. Based on this finding, the "AND" definition should certainly not be used as the collision avoidance region definition for DAA systems.

Table 3 Summary of undesirable situations

Parameter"	"AND"	"OR"	"OR-h"
TCAS RA before collision avoidance region crossing	6.2%	0%	0%
TCAS RA without collision avoidance region crossing	16.5%	0%	0%
Collision avoidance region crossing without TCAS RA	65.5%	69.1%	71.2%
Collision avoidance region crossing before DAA Warning alert	0.1%	23.8%	3.2%
Collision avoidance region crossing without DAA Warning alert	31.4%	36.4%	39.7%

A closer investigation of these encounter situations found that there were two main causes. In the first undesirable situation, the flights were (separated close horizontally and) separated vertically by about 400-600 ft, which was close enough for the intruder aircraft's TCAS system to issue an RA. Due to the slow vertical convergence rate of the two aircraft of 500 ft/min, though, the vertical tau was greater than 50 seconds, which exceeded the threshold needed for the "AND" definition of the collision avoidance region to be crossed. However, the "OR" and "OR-h" collision avoidance regions were crossed because the "vertical separation at CPA" and "current vertical separation" conditions were met (in addition to the modified tau condition).

In the second undesirable situation, the ownship and intruder aircraft were both flying level and separated vertically by less than 600 ft, which was close enough for the intruder aircraft's TCAS system to issue an RA. However, since the vertical convergence rate was zero, the vertical tau was undefined. As such, the "AND" collision avoidance region definition was not crossed. However, the "OR" and "OR-h" collision avoidance regions were crossed because the "vertical separation at CPA" and "current vertical separation" conditions were met (in addition to the modified tau condition).

Results Supporting "OR-h" Collision Avoidance Region Definition

The other interoperability metrics will be used to decide between the "OR" and "OR-h" definitions. First, note that the percentage of encounters with collision avoidance region crossing that also have a subsequent DAA Warning alert is only 3.2% when using the "OR-h" definition compared to 23.8%

when using the "OR" definition (see fourth row of Table 3). The lower value when using the "OR-h" definition is preferred because the ownship and intruder aircraft are typically far enough apart in these cases at the initial DAA Warning alert that the DAA system can provide either horizontal or vertical guidance without the risk of conflicting with RAs that could be issued by the intruder aircraft's TCAS system. By comparison, the other undesirable situations in which the collision avoidance region is too conservative (see third and fifth rows of Table 3) are only slightly higher when using the "OR-h" definition than when using the "OR" definition. Based on this analysis, the "OR-h" collision avoidance region definition should be used by DAA systems because it has the lowest overall level of non-interoperability with both TCAS RAs and DAA Warning alerts.

Table 4 shows the prevalence of desirable situations for each of the three collision avoidance region definition candidates. First, note that 94.7% of DAA Warning alerts occur before the collision avoidance region is crossed when using the "OR-h" definition compared to 63.2% when using the "OR" definition (see second row of Table 4). The higher value when using the "OR-h" definition is preferred in these cases because the DAA system will have the freedom to determine the best maneuver guidance for the ownship whether it be in the horizontal domain or the vertical domain without the risk of conflicting with RAs that could be issued by the intruder aircraft's TCAS system. By comparison, the other desirable situation where the collision avoidance region is crossed before TCAS RA is issued is only slightly lower when using the "OR-h" definition than when using the "OR" definition (see first row of Table 4). In summary, the analysis of the desirable situations indicates that the "OR-h" collision avoidance region definition should be used because it has the highest overall level of interoperability with both TCAS RAs and DAA Warning alerts.

Table 4 Desirable situations

Parameter"	"AND"	"OR"	"OR-h"
Collision avoidance region crossing before TCAS RA	32.0%	30.8%	28.7%
DAA Warning alert before collision avoidance region crossing	78.9%	63.2%	94.7%

Concluding Remarks

To prevent the ownship aircraft's DAA system from providing vertical guidance that could conflict with RAs issued by the intruder aircraft's TCAS system, the collision avoidance region should be large enough to encompass all geometries that would trigger a TCAS RA (i.e., the TCAS RA region). At the same time, the collision avoidance region should also be small enough to avoid limiting DAA vertical guidance when the ownship and intruder are outside of the TCAS RA region at initial DAA Warning alert.

The results of an unmitigated factorial encounter analysis of 1.3 million simulated pairs indicate that the "OR-h" collision avoidance region definition achieved these dual objectives the best overall. These results were presented at the RTCA SC-228 July 2016 meeting with the recommendation to utilize the "OR-h" collision avoidance region definition. After consulting with TCAS II experts at MIT-Lincoln Laboratories and the MITRE Corporation who concurred with the research findings, the "OR-h" definition below is now being used in the RTCA SC-228 MOPS for UAS DAA systems:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } (0 \le \tau_v < \tau^*_v \text{ OR } h < h^*)$$

with ("OR-h")

$\tau^*_{\text{mod}} = 50$ seconds, $DMOD$ = 1.1 NM, $\tau^*_v = 50$ seconds, and $h^* = 800$ ft