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Ensuring Interoperability between UAS Detect-and-Avoid and Manned Aircraft Collision Avoidance

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***Abstract*— The UAS community in the United States has identified the need for a "collision avoidance region" in which UAS Detect-and-Avoid (DAA) vertical guidance is restricted to preclude interoperability issues with manned aircraft collision avoidance system vertical resolution advisories (RAs). This paper documents the process by which the collision avoidance region was defined. Three candidate definitions were evaluated on 1.3 million simulated pairwise encounters between UAS and manned aircraft covering a wide range of horizontal and vertical closure rates, angles, and miss distances. Each definition was evaluated with regard to UAS DAA interoperability with manned aircraft collision avoidance in terms of how well it achieved: 1) the primary objective of restricting DAA vertical guidance prior to RAs when the aircraft are close, and 2) the secondary objective of avoiding unnecessary restrictions of DAA vertical guidance at a DAA alert when the aircraft are further apart. The collision avoidance region definition that fully achieves the primary objective and best achieves the secondary objective was recommended to and accepted by the UAS community in the United States. By this definition, UAS and manned aircraft are in the collision avoidance region—during which DAA vertical guidance is restricted—when the time to closest point of approach (CPA) is less than 50 seconds and either the time to co-altitude is less than 50 seconds or the current vertical separation is less than 800 feet.**

Keywords- unmanned aircraft systems; interoperability; detect-and-avoid; well clear; collision avoidance; resolution advisories

NOMENCLATURE

DMOD	distance modification
HMD	horizontal miss distance (at CPA)
HMD^*	horizontal miss distance (at CPA) threshold
ZTHR	vertical separation (at horizontal CPA)
$ZTHR^*$	vertical separation (at horizontal CPA) threshold
d_h	vertical separation (current)
d_h^*	vertical separation threshold (current)
d_x	horizontal separation in x-dimension
d_y	horizontal separation in y-dimension
r	slant range
$\dot{r}$	slant range rate
r_{xy}	horizontal range
$\dot{r}_{xy}$	horizontal range rate
t_{CPA}	time to horizontal CPA
v_{rh}	relative vertical velocity
v_{rx}	relative horizontal velocity in x-dimension
v_{ry}	relative horizontal velocity in y-dimension
τ_{mod}	horizontal modified tau
τ_{mod}^*	horizontal modified tau threshold
$\tau_{\text{mod\_r}}$	slant range modified tau
τ_v	vertical tau
τ_v^*	vertical tau threshold

I. INTRODUCTION

A consortium of industry, government, and academic institutions in the United States named RTCA Special Committee-228 (SC-228) has developed Minimum Operational Performance Standards (MOPS) for Unmanned Aircraft Systems (UAS) [1]. The Federal Aviation Administration (FAA) in the United States will utilize these MOPS to develop regulations for Detect-And-Avoid (DAA) systems and other equipment necessary for UAS to meet aviation regulations to remain "well clear" of other aircraft, some of which may be equipped with an onboard collision avoidance system: Traffic Alert and Collision Avoidance System (TCAS) in the United States and Airborne Collision Avoidance System (ACAS) in Europe.

In safety-critical situations such as Loss of Well Clear (LOWC) and Near Mid-Air Collision (NMAC) when UAS are in closest proximity with manned aircraft, interoperability between UAS DAA systems and manned aircraft collision avoidance systems is crucial. In particular, UAS DAA systems must not provide guidance that is incompatible with guidance that manned aircraft may receive from onboard collision avoidance systems (i.e., Resolution Advisories, or RAs). Otherwise, the UAS may maneuver in a way which conflicts with manned aircraft collision avoidance RA maneuvers.

The highly safety-critical topic of interoperability between UAS DAA systems and manned aircraft collision avoidance systems was first explored in-depth in an ATM2015 paper [2] in which millions of encounters between UAS and manned aircraft were simulated and evaluated. The author found that when UAS guidance was not coordinated with manned aircraft TCAS RAs, UAS vertical rate changes greater than 500 feet per minute (ft/min) in close-proximity situations resulted in higher likelihood of NMAC. This study was the basis for the inclusion in the RTCA SC-228 preliminary draft MOPS [3] of a Collision Avoidance (CA) Region within which UAS DAA vertical guidance is restricted.

At the request of RTCA SC-228, NASA evaluated the definition of the CA region in the preliminary draft MOPS in terms of interoperability with manned aircraft collision avoidance system RAs (Section III). In addition to this, NASA also developed and evaluated two alternative definitions for the CA region based on careful study of the definitions of TCAS RA (Section II.C) and DAA alerting (Section II.B). This was carried out because differences between the CA region definitions and the TCAS II sensitivity level (SL) definitions for RAs could significantly affect the degree of interoperability between UAS DAA systems and manned aircraft collision avoidance systems [4].

All three CA region definition candidates were evaluated on 1.3 million simulated pairwise encounters between UAS and manned aircraft covering a wide range of horizontal and vertical closure rates, angles, and miss distances that could occur in the airspace, including rare “corner cases.” This paper documents the results of this research in recommending a CA region definition that was accepted by RTCA SC-228 for the UAS DAA MOPS [1].

II. Background

A. UAS Well-Clear Definition

The second FAA-sponsored Sense-and-Avoid (SAA) Workshop defined SAA as “the capability of a UAS to remain well clear from, and avoid collisions with, other airborne traffic” [5]. The current study uses the term “detect and avoid” (DAA) instead of SAA because the UAS community in the United States transitioned to DAA with no change in meaning since the publication of the workshop report.

The SAA Science and Research Panel (SARP) in the United States coordinated parallel research efforts by NASA, the Massachusetts Institute of Technology Lincoln Laboratory, and the United States Air Force Research Laboratory to develop a quantitative definition for UAS well clear [6]. Several well clear definition candidates were evaluated by a variety of methods, including an approach based on the safety risk of the relative geometry between UAS and other aircraft [7]. Based on the results of these analyses, a well clear definition was recommended to RTCA SC-228 and the FAA. After incorporating feedback from both institutions, a consensus on the definition of well clear for UAS was reached. By this definition, a loss of well clear (LOWC) is an event in which a UAS is in close proximity with another aircraft such that the following three conditions are concurrently true [1]:

1. $d_h \le d_h^*$ where $d_h^* = 450$ ft
2. $HMD < HMD^*$ where $HMD^* = 4000$ ft
3. $\tau_{\text{mod}} < \tau^*_{\text{mod}}$ where $\tau^*_{\text{mod}} = 35$ sec and $DMOD = 4000$ ft

Figure 1 illustrates the variables and parameters used to define well clear for UAS.

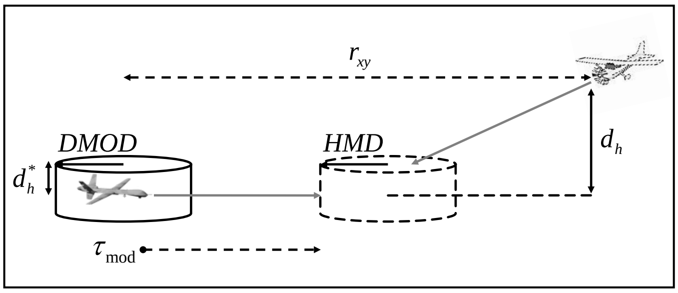

Figure 1. *Schematic of the types of variables and parameters used to define UAS well clear as well as the collision avoidance region*

The UAS well clear definition uses a spatial threshold in the vertical dimension known as d_h^* to which the current vertical separation between the two aircraft ($d_h = |h_2 - h_1|$) is compared.

The well clear definition also utilizes a spatial metric in the horizontal dimension known as the horizontal miss distance (*HMD*), which is defined as the projected separation in the horizontal dimension at the predicted close point of approach (CPA):

$$HMD = \begin{cases} \sqrt{(d_x + v_{rx}t_{CPA})^2 + (d_y + v_{ry}t_{CPA})^2} & \text{for } t_{CPA} \ge 0 \\ -\infty & \text{for } t_{CPA} < 0 \end{cases}$$

where

$d_x = x_2 - x_1$ (horizontal separation in x-dimension)

$d_y = y_2 - y_1$ (horizontal separation in y-dimension)

$v_{rx} = \dot{x}_2 - \dot{x}_1$ (relative horizontal velocity in x-dimension)

$v_{ry} = \dot{y}_2 - \dot{y}_1$ (relative horizontal velocity in y-dimension)

$$t_{CPA} = \max(0, \ -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2})$$

Note that v_{rx} and v_{ry} are negative when aircraft are converging

The well clear definition also uses a temporal separation metric known as “modified tau” or τ_{mod} which estimates the time to CPA between two aircraft. Modified tau is adopted from the collision detection logic of the Traffic Alert and Collision Avoidance System (TCAS) [8] that is on board manned aircraft.

Modified tau is based on the concept of "tau" (τ), which is calculated as the ratio of slant range (r) between aircraft to their slant range rate ($\dot{r}$) and measured in seconds:

$$\tau = -r / \dot{r}$$

where

$$r = \sqrt{r_{xy}^2 + d_h^2}$$

$$r_{xy} = \sqrt{d_x^2 + d_y^2}$$

Note that $\dot{r}$ is negative when aircraft are converging

Note that τ is positive when aircraft are converging

As described in the TCAS II Manual [9], one issue with the tau metric is that the calculated tau can be large even when the physical separation between two aircraft is small if the rate of closure is low (e.g., two flights flying at about the same speed, on the same heading, and offset by a small distance). In situations like this, the calculated tau value does not ensure adequate separation between two aircraft because a sudden trajectory change that increases the closure rate (e.g., a turn) would not provide sufficient alerting time to avoid LOWC. To provide protection for these types of situations, a modified alerting threshold referred to as "modified tau" was developed for use in TCAS II. Modified tau utilizes a parameter known as "distance modification" (*DMOD*) to provide a minimum threat range boundary encircling the ownship aircraft that triggers an alert regardless of the calculated value of tau.

In TCAS II, modified tau ($\tau_{\text{mod\_r}}$) is calculated using slant range (r) and slant range rate ($\dot{r}$). By comparison, during the second FAA-sponsored Sense-and-Avoid (SAA) Workshop [5], it was decided that modified tau (τ_{mod}) in the DAA well clear definition be calculated based on horizontal range (r_{xy}) and horizontal range rate ($\dot{r}_{xy}$) and measured in seconds as follows:

$$\tau_{\text{mod}} = \begin{cases} 0 & \text{when } r_{xy} \le DMOD \\ -\dfrac{(r_{xy}{}^2 - DMOD^2)}{r_{xy}\dot{r}_{xy}} & \text{for } r_{xy} > DMOD \text{ when } \dot{r}_{xy} > DMOD \\ \text{inf} & \text{for } r_{xy} > DMOD \text{ when } \dot{r}_{xy} > DMOD \end{cases}$$

where

DMOD is a constant, and

$$\dot{r}_{xy} = \frac{d_x v_{rx} + d_y v_{ry}}{r}$$

B. DAA Warning 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 nmi 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 of 35 sec and 450 ft, respectively, are the same as in the well clear definition.

In the simulations conducted for this study, DAA Warning alerts were issued when the following set of conditions were predicted to occur within 40 seconds in the future, which is the sum of the 25-second minimum average time of alert for the Hazard Zone of DAA Warning alerts [1] and a 15-second buffer that a DAA system might use to guard against the effects of aircraft trajectory uncertainty:

$$0 \le \tau_{\text{mod}} < \tau^*_{\text{mod}} \text{ AND } HMD < HMD^* \text{ AND } d_h < d_h{}^*$$

with

$$\tau^*_{\text{mod}} = 35 \text{ sec, } DMOD = 0.75 \text{ nmi, } HMD^* = 0.75 \text{ nmi, and } d_h{}^* = 450 \text{ ft}$$

C. TCAS

This study utilized 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. (See next section for definitions.) The spatial and temporal thresholds utilized by TCAS II are listed in Table I. (See [8] for additional details.)

TABLE I. TCAS II VERSION 7.1 SENSITIVITY LEVEL (SL) DEFINITIONS AND THRESHOLDS FOR RESOLUTION ADVISORIES

Manned Aircraft Altitude (ft)	**SL**	**Tau (sec)**	**DMOD (nmi)**	**ZTHR (ft)**	**ALIM (ft)**
< 1000 (AGL)	2	N/A	N/A	N/A	N/A
1000-2350 (AGL)	3	15	0.20	600	300
2350-5000	4	20	0.35	600	300
5000-10000	5	25	0.55	600	350
10000-20000	6	30	0.80	600	400
20000-42000	7	35	1.10	700	600
> 42000	7	35	1.10	800	700

The tau thresholds listed in Table I are for both modified tau and vertical tau (τ_v). The latter is defined as:

$$\tau_v = -\frac{d_h}{v_{rh}}$$

where

$$d_h = |h_2 - h_1|$$

$$v_{rh} = \dot{h}_2 - \dot{h}_1$$

D. Collision Avoidance Region Definition Candidates

UAS are projected to interact with manned aircraft on a regular basis [10], [11], [12]. In fact, the latter study estimated that UAS and manned VFR aircraft could experience Loss of Well Clear (LOWC) separation at an unacceptable rate of about once every 50 UAS flight hours in the absence of UAS DAA systems.

In safety-critical situations like LOWC and Near Mid-Air Collision (NMAC) when UAS are in close proximity with manned aircraft, interoperability between UAS DAA systems and manned aircraft collision avoidance systems is essential as shown in [2]. This study was the basis for the inclusion in the RTCA SC-228 preliminary draft MOPS [3] of a Collision Avoidance (CA) Region within which UAS DAA vertical guidance is restricted if the UAS does not have Vertical RA Complement (VRC) data (e.g., "do not climb") from the manned aircraft's collision avoidance system. To prevent the UAS from maneuvering to maintain or regain DAA well clear in a way that could be incompatible with the manned aircraft's collision avoidance maneuver in this situation, UAS DAA guidance is restricted in two ways: 1) no vertical altitude guidance is provided, and 2) no vertical speed guidance greater than the current vertical speed ±500 ft/min is provided.

The collision avoidance region must be sufficiently large to encompass all geometries that would trigger a TCAS RA (i.e., the TCAS RA region). That is, UAS and manned aircraft must always enter the CA region prior to any TCAS RAs issued by manned aircraft onboard collision avoidance systems in line with the interoperability principles described in [4] and [13]. However, the CA region also should not be so large as to limit DAA vertical guidance unnecessarily at a DAA Warning alert when the two aircraft are outside of the safety-critical TCAS RA region.

Three CA region definition candidates were evaluated in this paper. First, the "AND" collision avoidance region definition below was developed based on research presented at ATM2015 [2] for the preliminary RTCA SC-228 draft MOPS [3]. In addition, two alternative definitions ("OR" and "OR-h") were developed in this study based on careful study of the definitions of TCAS RA (Section II.C) and DAA alerting (Section II.B). All three CA region definition candidates were evaluated in terms of how well they achieved the competing dual interoperability objectives described in the previous paragraph. These definitions utilize some but not all of the same types of parameters in the TCAS RA sensitivity level and DAA Warning alerting definitions discussed in the previous two sections.

1. The "AND" definition of the collision avoidance region has a form that is like the DAA alerting definition that connects all conditions by "AND" operators. (See Section II.B.) It does not fully encompass the TCAS RA region, though, since the two vertical conditions are connected by an "AND" operator instead of an "OR" operator (verified by TCAS II experts at the Massachusetts Institute of Technology-Lincoln Laboratory and the MITRE Corporation in the United States):

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

with

$$\tau^*_{\text{mod}} = 50 \text{ sec}, DMOD = 1.1 \text{ nmi}, \ \tau^*_v = 50 \text{ sec, and } ZTHR^* = 800 \text{ ft}$$

RTCA SC-147 chose the threshold parameter values for the RTCA SC-228 UAS DAA MOPS [1]. These values correspond to the highest TCAS II RA sensitivity level (i.e., last row of Table I). The tau values in the "AND" collision avoidance region definition include 15 seconds for pilot response and TCAS II altitude tracker response [3].

2. The "OR" definition connects the two vertical conditions by an "OR" operator instead of an "AND" operator in order to fully encompass the TCAS RA region:

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

with

$$\tau^*_{\text{mod}} = 50 \text{ sec}, DMOD = 1.1 \text{ nmi}, \ \tau^*_v = 50 \text{ sec, and } ZTHR^* = 800 \text{ ft}$$

3. The "OR-h" definition also fully encompasses the TCAS RA region like the "OR" definition. They differ in that the "OR-h" definition uses a "current vertical separation" (d_h) condition as in the DAA alerting definition instead of a "vertical separation at CPA" (*ZTHR*) condition:

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

with

$$\tau^*_{\text{mod}} = 50 \text{ sec}, DMOD = 1.1 \text{ nmi}, \ \tau^*_v = 50 \text{ sec, and } d_h^* = 800 \text{ ft}$$

III. EXPERIMENT SETUP

A. Encounter Set

The three collision avoidance region definition candidates were evaluated on 1.3 million simulated pairwise encounters between UAS and manned aircraft that cover all combinations of the parameters in Table II. This encounter set is appropriate for this study on interoperability between UAS DAA systems and manned aircraft collision avoidance systems because it captures a wide range of horizontal and vertical closure rates, angles, and miss distances that could occur in the airspace. The combinatorial approach was utilized because it naturally includes the rare "corner cases" that may not occur on a regular basis in the airspace.

TABLE II. TEST PARAMETERS FOR UAS AND MANNED AIRCRAFT

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

In each encounter, the UAS was simulated flying level at altitude 5000 ft heading north. The UAS ground speeds ranged between 50 and 200 kts to cover the expected performance range of UAS aircraft. To span the range of possible encounter situations, manned aircraft flying level as well as manned aircraft climbing and manned aircraft descending at vertical speeds up to 2000 ft/min were simulated (Figure 2). In addition, manned aircraft flying at speeds between 50 and 250 kts in encounters at a wide range of angles relative to the UAS from the front, rear, and sides were also simulated (Figure 3). Furthermore, encounters with CPA distances from 0 nmi horizontally and 0 ft vertically up through 1.5 nmi horizontally and 1000 ft vertically were also simulated (Figures 4 and 5). Lastly, guidance information for the UAS aircraft using different trial plan turn rates and climb and descent values was also collected.

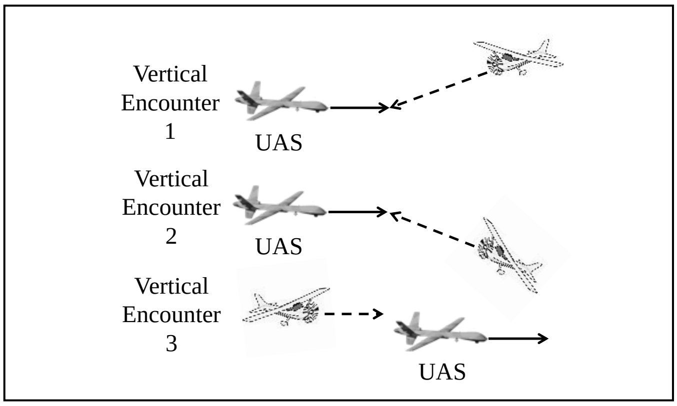

Figure 2. *Schematic of representative simulated encounters with manned aircraft intruders: 1) descending toward the UAS, 2) climbing toward the UAS, and 3) flying level with a vertical offset relative to the UAS*

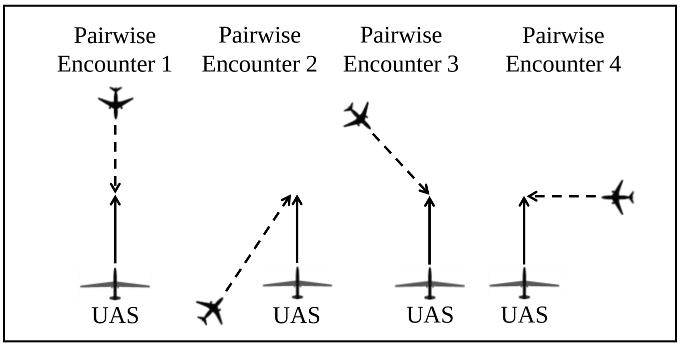

Figure 3. *Schematic of representative simulated encounters with manned aircraft intruders converging toward the UAS: 1) from the front, 2) from the rear, 3) from the left, and 4) from the right*

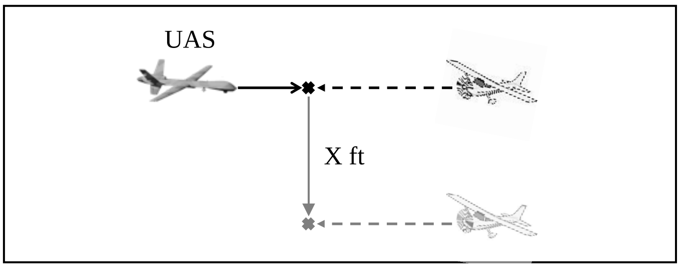

Figure 4. *Schematic of encounters with vertical offset (gray) and without vertical offset (black)*

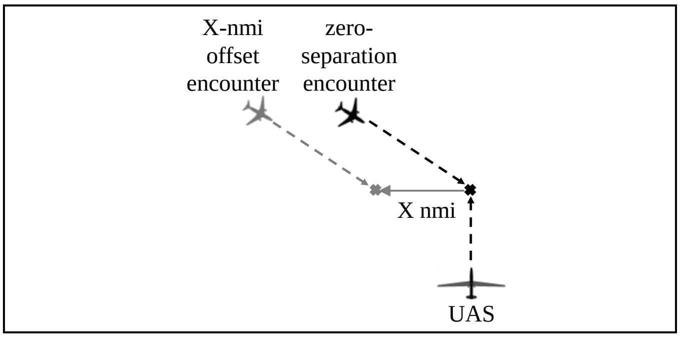

Figure 5. *Schematic of encounters with horizontal offset (gray) and without horizontal offset (black)*

B. *Simulation Features*

All encounters were simulated without uncertainty and without mitigations performed by either UAS or manned aircraft to ensure that the sequences of DAA Warning alerts, collision avoidance region crossings, and TCAS RAs were entirely determined by encounter geometries. This is suitable for identifying and resolving the major interoperability issues between UAS DAA systems and manned aircraft collision avoidance systems. However, higher-fidelity simulations with realistic surveillance, sensor, and tracker models, DAA mitigations (as in [14]), and/or TCAS mitigations are needed to investigate and inform other aspects of the RTCA SC-228 MOPS (e.g., alerting).

C. Interoperability Metrics

This study evaluates the three collision avoidance region definition candidates in terms of their interoperability with TCAS RAs and DAA Warning alerts. More specifically, this study analyzes when collision avoidance region thresholds are crossed (if ever) relative to when TCAS RAs and DAA Warning alerts are issued (if ever). The interoperability of the collision avoidance region with TCAS RAs is the most important consideration because this is when UAS and manned aircraft are in closest proximity and safety is most critical.

1) Interoperability between Collision Avoidance Region and TCAS Resolution Advisories

It is essential that vertical guidance provided by the UAS DAA system be restricted to prevent conflicts with TCAS RAs issued by the manned aircraft's TCAS system. To do this, the CA region threshold must always be crossed before a TCAS RA is issued. There should not be any encounters in which a TCAS RA is issued before the CA region threshold is crossed, and there also should not be any cases in which a TCAS RA is issued but the CA region threshold is never crossed. CA region candidate definitions that allow these undesirable situations to occur are unacceptable.

The corresponding metrics utilized to evaluate the collision avoidance region definition candidates are:

1. Out of the encounters in which a TCAS RA is issued, the percentage with a TCAS RA issued before the CA region is crossed
2. Out of the encounters in which a TCAS RA is issued, the percentage without the CA region being crossed

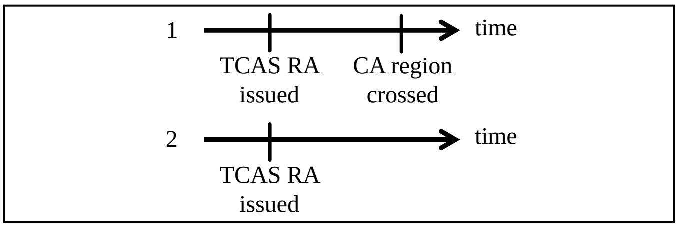

Figure 6. *Illustration of event sequences analyzed for interoperability between CA region and TCAS RAs*

The denominator for both of these metrics is the number of encounters in which TCAS RA is issued: 343,100. This was the same for each collision avoidance region definition candidate because all simulated encounters were unmitigated (i.e., no maneuvers).

2) Interoperability between Collision Avoidance Region and DAA Warning Alerts

As a secondary objective, the CA region should not be so large as to limit DAA vertical guidance unnecessarily at a DAA Warning alert. Ideally, there would not be any cases in which the CA region is crossed before a DAA Warning alert is issued. In addition, a DAA Warning alert ideally would always be issued before the CA region is crossed. However, since the UAS and manned aircraft are separated more at the time that DAA Warning alerts are issued than at the time that TCAS RAs are issued, the corresponding metrics do not necessarily have to be 0% and 100%, respectively:

1. Out of the encounters in which the CA region is crossed, the percentage with the CA region crossed before a DAA Warning alert is issued
2. Out of the encounters with DAA Warning alert issued, the percentage with a DAA Warning issued before the CA region is crossed

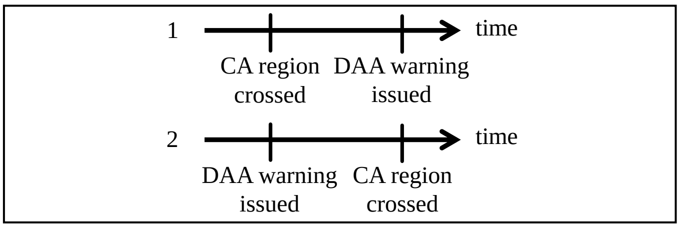

Figure 7. *Illustration of event sequences analyzed for interoperability between CA region and DAA Warning alerts*

These two metrics are used to decide between CA region definition candidates that do not allow either of the undesirable interoperability situations between the CA region and TCAS RAs to occur (described in Section III.C.1).

The denominator for the first of these metrics is the number of encounters in which the CA region is crossed, which varies by CA region definition candidate. This number was 829,380 for the "AND" definition, 1,113,180 for the "OR" definition, and 1,194,080 for the "OR-h" definition. On the other hand, the denominator for the second of these metrics is the number of encounters with DAA Warning alert, which was the same for each CA region definition candidate because all simulated encounters were unmitigated (i.e., no maneuvers).

3) Summary

Table III summarizes the set of undesirable and desirable interoperability situations analyzed in this paper. The first two rows are the undesirable interoperability situations described in Section III.C.1 that correspond to the primary interoperability objective for the CA region to be large enough to encompass all geometries that lead to TCAS RA on the manned aircraft (*). The other rows of Table III correspond to the competing secondary interoperability objective for the CA region to not be so large as to limit DAA vertical guidance unnecessarily at a DAA Warning alert (**).

TABLE III. TYPES OF INTEROPERABILITY SITUATIONS ANALYZED

Type	Description
Undesirable	TCAS RA issued, then CA region crossed*
	TCAS RA issued without CA region crossed*
	CA region crossed, then DAA Warning alert issued**
Desirable	DAA Warning alert issued, then CA region crossed**

IV. RESULTS

The first two interoperability metrics in Table III are the most important for evaluating the three collision avoidance region definitions (Section VI.A): 1) the percentage of encounters with a TCAS RA in which the CA region was crossed after a TCAS RA was issued, and 2) the percentage of encounters with a TCAS RA in which the CA region was never crossed. These metrics capture the most safety-critical situations when the UAS and manned aircraft were in closest proximity such that the vertical guidance provided by the UAS DAA system must not conflict with RAs issued by the manned aircraft's TCAS system. Any CA region definition for which these metrics are greater than zero is not suitable for use. After excluding all unsuitable CA region definition candidates, the remaining ones are evaluated (Section IV.B) in terms of having the lowest value for the last undesirable metric in Table III and the highest value overall for the desirable metric in Table III.

A. Results Invalidating the "AND" Collision Avoidance Region Definition

Table IV shows the prevalence of encounter situations with undesirable events for each CA region definition candidate. The most important difference between them is that the "AND" definition is the only one with the highly undesirable cases in which a TCAS RA was issued before the CA region was crossed or a TCAS RA was issued without the CA region being crossed (first two rows of the "AND" column in Table IV). Based on these results, the "AND" definition should certainly not be used as the CA region definition for DAA systems because it does not encompass all geometries that trigger TCAS RAs. As such, the "AND" definition could allow for UAS DAA vertical guidance that is incompatible with manned aircraft TCAS RAs. By comparison, these undesirable cases never occurred when using the "OR" and "OR-h" CA region definitions (the 0% values in Table IV).

TABLE IV. SUMMARY OF UNDESIRABLE SITUATIONS (LOWER PERCENTAGE IS PREFERRED)

Undesirable Situation	"AND"	"OR"	"OR-h"
TCAS RA issued, then CA region crossed	6.2%	0%	0%
TCAS RA issued without CA region crossed	16.5%	0%	0%
CA region crossed, then DAA Warning Alert issued	0.1%	23.8%	3.2%

Since the results in this section indicate that the "AND" collision avoidance region definition is unsuitable for DAA systems, Section IV.B will only compare the performance of the "OR" and "OR-h" CA region definitions. The one having the highest overall interoperability with manned aircraft TCAS RAs and UAS DAA Warning alerts was recommended to RTCA SC-228. However, before delving into that analysis, the two most frequent types of encounter geometries which disqualified the "AND" CA region definition from contention are illustrated and discussed next.

1) Investigation of encounter geometry in which a TCAS RA was issued before the CA region was crossed

One type of encounter geometry was prevalent among the cases in which a TCAS RA was issued on the manned aircraft before the "AND" CA region was crossed. In this situation, the two aircraft were separated vertically between 420 ft and 600 ft, which was close enough to trigger a TCAS RA on the manned aircraft. However, since the manned aircraft was converging vertically toward the UAS at a slow rate of 500 ft/min, UAS DAA vertical guidance was not restricted when using the "AND" definition of the CA region because the vertical tau exceeded the 50-second maximum threshold.

Figure 8 illustrates one representative example in which vertical tau was 71 sec because the manned aircraft was 592 ft above the UAS and descending toward the UAS at a rate of 500 ft/min. The two aircraft were sufficiently close both spatially and temporally to trigger a TCAS RA on the manned aircraft. However, the "AND" CA region *was not* crossed because the vertical tau of 71 sec was greater than the 50-second maximum threshold. On the other hand, the "OR" and "OR-h" CA regions *were* crossed in this zero-horizontal-separation case. With regard to the former, its modified tau condition was met (0 sec) and the vertical separation of 0 ft at horizontal CPA was less than its maximum threshold of 800 ft. With regard to the latter, its modified tau condition was met (0 sec) and the current vertical separation of 592 ft was less than its maximum threshold of 800 ft.

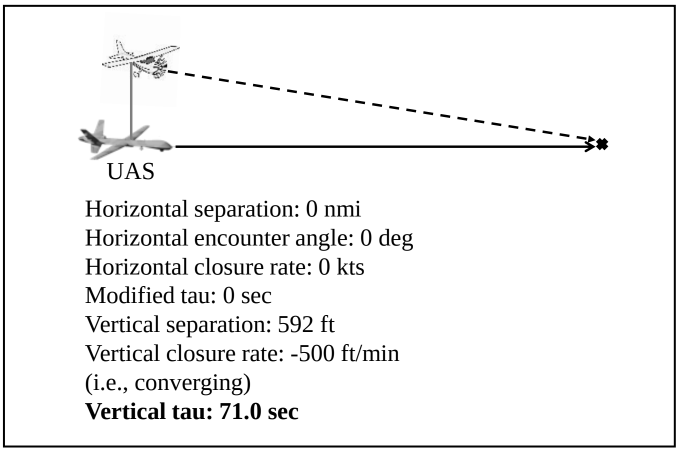

Figure 8. *Schematic of representative slow-vertical-convergence case with a TCAS RA issued before the "AND" CA region was crossed because vertical tau exceeded the maximum threshold of 50 seconds*

2) Investigation of encounter geometry in which a TCAS RA was issued without the CA region ever being crossed

One type of encounter geometry was prevalent among the cases in which a TCAS RA was issued without the "AND" CA region ever being crossed. In this situation, the UAS and the manned aircraft were both flying level and separated vertically by less than 600 ft, which was close enough for the manned aircraft's TCAS system to issue an RA. However, since the vertical convergence rate was zero, vertical tau was undefined and, thus, the "AND" CA region was never crossed.

Figure 9 illustrates one representative example in which vertical tau was undefined because the UAS and the manned aircraft were both flying level at 5000 ft with vertical rate of 0 ft/min. The two aircraft were close enough both spatially and temporally to trigger a TCAS RA on the manned aircraft, but the "AND" CA region *was never* crossed because vertical tau was undefined since the vertical convergence rate was zero. On the other hand, both the "OR" and the "OR-h" CA regions *were* crossed because the vertical separation at CPA of 0 ft ("OR") and the current vertical separation of 0 ft ("OR-h") were both less than their respective 800-ft maximum thresholds in addition to the modified tau condition being met.

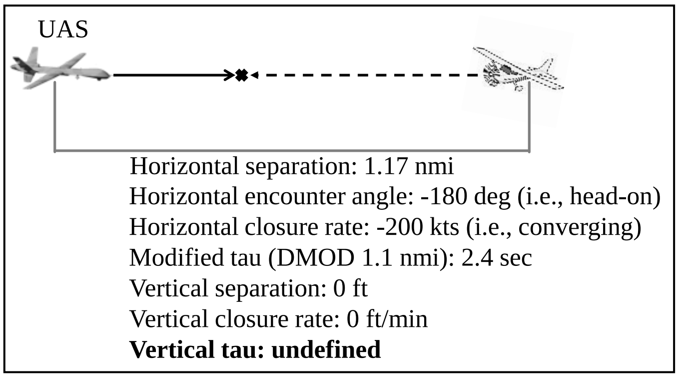

Figure 9. *Schematic of representative zero-vertical-convergence case with a TCAS RA issued before the "AND" CA region was crossed because vertical tau was undefined*

B. Results Supporting the "OR-h" Collision Avoidance Region Definition

This section compares the results for the "OR" and "OR-h" CA region definitions in terms of their interoperability with UAS DAA Warning alerts. The first result to be discussed is the prevalence of encounters in which the CA region was crossed before a DAA Warning alert was issued. In these undesirable situations, the CA region was overly large and DAA vertical guidance for the UAS would have been restricted unnecessarily at a DAA Warning alert even though the UAS and manned aircraft were outside of the safety-critical TCAS RA region. As seen in the bottom row of Table IV in Section IV.A, this metric is more than 20 percentage points lower for the "OR-h" definition than for the "OR" definition. This result supports using the "OR-h" CA region definition for UAS DAA systems because it had a lower degree of non-interoperability with DAA Warning alerts.

One type of encounter geometry was prevalent among the cases in which the "OR-h" CA region *was not* crossed prior to a DAA Warning alert, but the "OR" CA region *was* crossed prior to a DAA Warning alert. In this situation, the "OR-h" CA region *was not* crossed even though modified tau was less than 50 sec because the UAS and manned aircraft were vertically separated by at least 800 ft and the rate of vertical convergence was slow enough that vertical tau was greater than 50 sec. However, the "OR" CA region *was* crossed because the vertical convergence rate was fast enough that the predicted vertical separation at CPA was less than 800 ft.

Figure 10 illustrates one representative example in which the "OR" CA region *was* crossed because the modified tau of 49.5 sec and the predicted vertical separation at CPA of 0 ft were both less than their respective maximum thresholds of 50 sec and 800 ft. There was no DAA Warning alert at this time instance since the vertical separation between the two aircraft was predicted to be more than 450 ft for the entire 40-second look-ahead time window. DAA Warning alerts were issued later on as the aircraft converged. The "OR-h" CA region *was not* crossed at this point because the vertical tau of 61 sec and the current vertical separation of 2033 ft both exceeded their respective maximum thresholds of 50 sec and 800 ft.

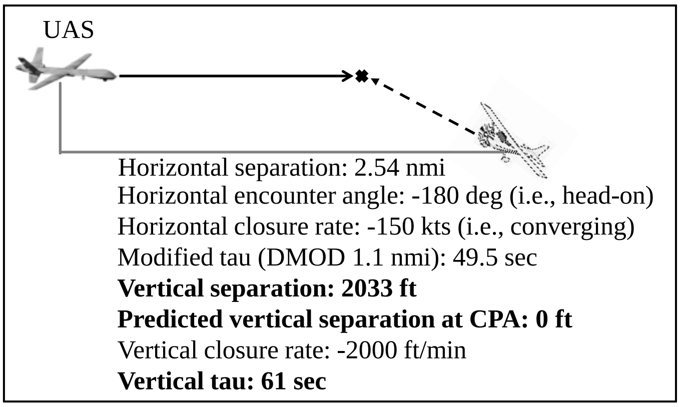

Figure 10. *Schematic of representative case in which the "OR" CA region was crossed before a DAA Warning alert, but the "OR-h" CA region was not crossed before a DAA Warning alert*

The second result analyzed is the prevalence of encounters with the desirable situation of the CA region being crossed after a DAA Warning was issued. In these cases, the CA region was not so large that DAA vertical guidance for the UAS would have been restricted unnecessarily at a DAA Warning alert.

Although the results for all three CA region definitions are included in Table V for completeness, the result for the "AND" CA region definition is not taken into consideration because the results in Table IV of Section IV.A already disqualified it from being considered for the UAS DAA MOPS. As seen in Table V, the metric is more than 30 percentage points higher when using the "OR-h" definition than when using the "OR" definition. This result supports using the "OR-h" CA region definition for UAS DAA systems because it had a higher degree of interoperability with DAA Warning alerts.

TABLE V. SUMMARY OF DESIRABLE SITUATIONS (HIGHER PERCENTAGE IS PREFERRED)

Number	"AND"	"OR"	"OR-h"
DAA Warning Alert issued, then CA region crossed	78.9%	63.2%	94.7%

C. Summary

Three CA region definition candidates were evaluated on 1.3 million simulated pairwise encounters between UAS and manned aircraft for a wide range of vertical and horizontal closure rates, angles, and miss distances. The "AND" CA region definition was determined to be unsuitable for the RTCA SC-228 MOPS because it did not encompass all encounter geometries that triggered TCAS RAs—primarily those with slow (e.g., 500 ft/min) or zero vertical convergence rates. As such, the "AND" CA region definition could allow for UAS DAA vertical guidance that is incompatible with manned aircraft TCAS RAs, which is unacceptable. Between the "OR" and "OR-h" CA region definitions, the other interoperability metrics indicated that the latter had a lower degree of non-interoperability and a higher degree of interoperability with DAA Warning alerts. Based on the results of this study, the "OR-h" CA region was recommended to RTCA SC-228 at its July 2016 meeting and accepted for use in the UAS DAA MOPS [1].

V. DISCUSSION

A. Altitude-Dependent Collision Avoidance Region Parameters

The data analysis results in Section IV indicate that the "OR-h" definition of the collision avoidance region has the lowest degree of non-interoperability and the highest degree of interoperability overall with regard to TCAS II Resolution Advisories and DAA Warning alerts. It may be possible to improve the interoperability of the "OR-h" CA region even further by making its threshold values state-dependent like TCAS II instead of utilizing constant values.

A set of altitude-dependent vertical separation threshold values is proposed in this section for follow-up research. The primary constraint is that each threshold value must be at least as large as its TCAS II RA counterpart to ensure safety. Using alternative threshold values for other conditions in the DAA-CA region definition such as modified tau, vertical tau, and DMOD could also further improve the interoperability of the "OR-h" CA region definition with manned aircraft TCAS RAs and DAA Warning alerts.

The "OR-h" definition of the CA region utilizes a constant vertical separation threshold value of 800 ft in all cases. This can lead to undesirable situations in which two aircraft cross into the "OR-h" CA region prior to DAA Warning alert. For instance, consider the situation in which the two aircraft are horizontally converging with modified tau less than 50 sec, vertically separated by at least 450 ft but less than 800 ft, and vertically diverging. In this case, they are in the "OR-h" CA region. However, there is no DAA Warning alert because the current vertical separation condition is never satisfied. Using the smaller, state-based TCAS II vertical separation threshold values in Table VI for the current vertical separation condition of the "OR-h" CA region definition could prevent a subset of these undesirable situations from occurring.

TABLE VI. VERTICAL SEPARATION THRESHOLD PARAMETERS

Manned Aircraft Altitude (ft)	TCAS SL	TCAS Value	"OR-h" Value	Proposed Value
< 1000 (AGL)	2	N/A	800	600
1000-2350 (AGL)	3	600	800	600
2350-5000	4	600	800	600
5000-10000	5	600	800	600
10000-20000	6	600	800	600
20000-42000	7	700	800	700
> 42000	7	800	800	800

B. Suitability of Suppressing Vertical Guidance for Non-Cooperative Manned Aircraft

This study investigated a method of suppressing UAS DAA vertical guidance to ensure interoperability with the collision avoidance systems of cooperative (i.e., transponder-equipped) manned aircraft. RTCA SC-228 also identified that it may be necessary at times to suppress UAS DAA vertical guidance in encounters with non-cooperative manned aircraft, which do not have a collision avoidance system by definition. In this scenario, the UAS can only use its radar system to track and estimate the state and projected path of non-cooperative VFR aircraft. This can lead to significant sensor errors, particularly when estimating vertical speed. This is especially problematic when regaining well clear separation since a poor maneuver choice could potentially result in mid-air collision between the UAS and non-cooperative VFR aircraft. Research is necessary to determine the circumstances under which suppressing DAA vertical guidance is necessary as well as the situations in which allowing DAA vertical guidance is beneficial (e.g., when the UAS is capable of maneuvering vertically at a faster rate than the propagation of the radar errors).

VI. CONCLUSIONS

Detect-and-avoid (DAA) systems enable unmanned aircraft systems (UAS) to remain "well clear" of other aircraft, some of which are manned aircraft equipped with a collision avoidance system. In the United States, private industry, government, and academia worked together in RTCA Special Committee-228 (SC-228) to develop minimum operational performance standards (MOPS) for UAS DAA systems. A safety-critical aspect of this work was ensuring that UAS DAA systems never provide guidance that is incompatible with manned aircraft collision avoidance resolution advisories (RAs). As part of this effort, this paper investigated three candidate definitions for a spatial-temporal “collision avoidance region” in which UAS DAA vertical guidance is restricted to preclude interoperability issues with manned aircraft collision avoidance RAs.

The collision avoidance region definitions were evaluated on 1.3 million simulated pairwise encounters between UAS and manned aircraft that covered a wide range of horizontal and vertical closure rates, angles, and miss distances which could occur in the airspace. One definition was disqualified because it was not large enough to prevent incompatible UAS DAA vertical guidance from ever being provided in safety-critical situations in which manned aircraft TCAS II systems issued vertical RAs. The two most prevalent types of encounter geometries in these cases involved either slow (e.g., -500 ft/min) or zero vertical convergence rates between the UAS and manned aircraft.

Of the remaining two CA region definition candidates, the one with the lowest degree of non-interoperability and the highest degree of interoperability with DAA alerts was recommended to RTCA SC-228 in July 2016. By this definition, two aircraft are in the collision avoidance region and UAS DAA vertical guidance is restricted when the time to closest point of approach (modified tau) is less than 50 seconds and either the time to co-altitude (vertical tau) is less than 50 seconds or the current vertical separation is less than 800 feet. TCAS II experts at the Massachusetts Institute of Technology-Lincoln Laboratory and the MITRE Corporation in the United States reviewed the research findings and concurred with the recommendation. RTCA SC-228 accepted the recommended collision avoidance region definition for use in the MOPS for UAS DAA systems to ensure interoperability between UAS detect-and-avoid and manned aircraft collision avoidance.

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