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UAS Well Clear Recovery against Non-Cooperative Intruders using Vertical Maneuvers

Andrew C. Cone[1] and David Thipphavong[2]
NASA Ames Research Center, Moffett Field, CA 94035

Seung Man Lee[3]
Crown Consulting Inc., Moffett Field, CA 94035

and

Confesor Santiago[4]
NASA Ames Research Center, Moffett Field, CA 94035

This paper documents a study that drove the development of a mathematical expression in the detect-and-avoid (DAA) minimum operational performance standards (MOPS) for unmanned aircraft systems (UAS). This equation describes the conditions under which vertical maneuver guidance should be provided during recovery of DAA well clear separation with a non-cooperative VFR aircraft. Although the original hypothesis was that vertical maneuvers for DAA well clear recovery should only be offered when sensor vertical rate errors are small, this paper suggests that UAS climb and descent performance should be considered—in addition to sensor errors for vertical position and vertical rate—when determining whether to offer vertical guidance. A fast-time simulation study involving 108,000 encounters between a UAS and a non-cooperative visual-flight-rules aircraft was conducted. Results are presented showing that, when vertical maneuver guidance for DAA well clear recovery was suppressed, the minimum vertical separation increased by roughly 50 feet (or horizontal separation by 500 to 800 feet). However, the percentage of encounters that had a risk of collision when performing vertical well clear recovery maneuvers was reduced as UAS vertical rate performance increased and sensor vertical rate errors decreased. A class of encounter is identified for which vertical-rate error had a large effect on the efficacy of horizontal maneuvers due to the difficulty of making the correct left/right turn decision: crossing conflict with intruder changing altitude. Overall, these results support logic that would allow vertical maneuvers when UAS vertical performance is sufficient to avoid the intruder, based on the intruder's estimated vertical position and vertical rate, as well as the vertical rate error of the UAS' sensor.

Nomenclature

DMOD	=	distance modification (used in the calculation of modified tau)
HMD	=	horizontal miss distance
HMD^*	=	horizontal miss distance threshold
d_h	=	vertical separation
d_h^*	=	vertical separation threshold
d_x	=	horizontal separation in the x-dimension
d_y	=	horizontal separation in the y-dimension

[1] Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Moffett Field, CA, 94035, AIAA Member.
[2] Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Moffett Field, CA, 94035, AIAA Member.
[3] Senior Scientist, Mail Stop 210-8, Moffett Field, CA, 94035, AIAA Member
[4] Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, Moffett Field, CA, 94035, AIAA Member.

r	=	slant range
$\dot{r}$	=	slant range rate
r_{xy}	=	horizontal range
$\dot{r}_{xy}$	=	horizontal range rate
t_{CPA}	=	time to horizontal closest point of approach
v_{rx}	=	relative horizontal velocity in the x-dimension
v_{ry}	=	relative horizontal velocity in the y-dimension
τ_{mod}	=	modified tau
τ^{*}_{mod}	=	modified tau threshold

I. Introduction

SAFE integration of unmanned aircraft systems (UAS) into the U.S. National Airspace System (NAS) requires that they interoperate with existing safety systems for manned aircraft. One requirement that is particularly difficult for UAS to satisfy is the requirement for aircraft to perform see-and-avoid to remain "well clear" of other aircraft.[1] This requirement is in the FAA's Federal Aviation Regulation §91.113(b), which dictates that, "When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft. When a rule of this section gives another aircraft the right of way, the pilot shall give way to that aircraft and may not pass over, under, or ahead of it unless well clear." §91.113 also covers right-of-way rules for air vehicle operations. If two aircraft get too close and lose "well clear," they are expected to maneuver immediately and attempt to regain it. However, the exact definition of the term "well clear" is not given in the regulations, and is subject to interpretation by the pilot. This is difficult for a UAS as there is not a pilot on board to make that determination of whether or not an aircraft is well clear.

The UAS equivalent to see-and-avoid—referred to as detect-and-avoid (DAA)[2]—is the subject of a body of work by RTCA Special Committee 228 (SC-228) and its member organizations, including NASA.[3,4] This group is creating the Minimum Operational Performance Standards (MOPS) for all aspects of UAS DAA systems, including but not limited to: surveillance, tracking, alerting, and guidance. This group is also creating an objective definition of "well clear" specifically for UAS, which will enable DAA systems to provide a UAS with guidance for avoiding other airborne traffic. This well clear definition is referred to as DAA Well Clear (DWC). The DAA system could be especially useful in relation to visual flight rules (VFR) traffic, as air traffic controllers will not always be able to provide separation services between those aircraft and a UAS.

A subset of VFR traffic does not transmit a secondary surveillance signal (e.g. Mode-C or Mode-S transponder) and does not broadcast any electronic information about itself to other aircraft. These are referred to as non-cooperative VFR flights. For these aircraft, UAS must track and estimate the position and state information of these non-cooperative "intruders" using only information from an air-to-air radar. Compared to cooperative VFR flights, radar data for these non-cooperative flights have significant errors in vertical rate and altitude. This is especially problematic when regaining DWC separation since a poor maneuver choice could potentially result in a near or actual mid-air collision. SC-228 decided that the best approach to mitigate this risk would be to suppress vertical maneuver guidance when attempting to regain DWC. The definition of DWC is given in Section II.

This paper documents the experiment NASA conducted in support of the development of this requirement. It examined the effects of suppressing vertical resolutions during DWC recovery against non-cooperative VFR aircraft. 108,000 encounters with a range of encounter geometries and potential UAS performance levels were analyzed. The results of this study led to the MOPS requirement to suppress UAS DAA vertical maneuver guidance for DWC recovery against non-cooperative VFR intruders when radar sensor errors exceed a threshold that is based on: 1) the potential climb and/or descent rate of the UAS, 2) the current estimated vertical rate of the non-cooperative VFR aircraft, and 3) the current vertical separation between the two aircraft. The equation is presented in Appendix A.

The rest of the paper is organized as follows. Section II defines a loss of DWC and a near mid-air collision (NMAC). Section III is the Design of Experiment, which includes information on the encounter sets, simulation platform, primary sensor, and metrics discussed in the paper. Section IV presents the results, while Section V discusses how large vertical-rate errors can significantly affect horizontal maneuvers for certain encounter geometries. Section VI is the Conclusion.

II. Background

The second FAA-sponsored Sense-and-Avoid (SAA) Workshop[5] defined SAA as "the capability of a UAS to remain DWC from, and avoid collisions with, other airborne traffic. SAA provides the intended functions of self separation (SS) and collision avoidance (CA) compatible with expected behavior of aircraft operating in the NAS." The SS function is intended to be a means of compliance with the regulatory requirements (14CFR Part 91, §91.111 and previously described §91.113) to "see and avoid" and remain "well clear" of other aircraft. The UAS community has transitioned to using the term "detect and avoid" rather than "sense and avoid" after publication of the workshop report and with no change in meaning. The rest of this paper uses DAA for consistency.

A. Loss of DAA Well Clear

The SAA workshop defined "well clear" as the state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a collision avoidance maneuver by the UAS or any other aircraft.[5] A set of definitions of well clear was proposed by a recent FAA report,[5] a dedicated U.S. government workshop on well clear,[2] and variations on methods utilized by the Traffic Collision and Avoidance System (TCAS II).[6,7] The UAS Executive Committee Science and Research Panel—coordinated research efforts by NASA, the Massachusetts Institute of Technology Lincoln Laboratory, and the U.S. Air Force Research Laboratory to compare the performance metrics and potential effect on the NAS when using these well clear definitions. Based on this work, the definition of DAA well clear shown in Eqn. (1) was recommended to RTCA Special Committee (SC)-228 and the FAA. After incorporating feedback from both organizations, a consensus on the definition of DAA well clear for UAS was reached.

According to this definition, loss of DAA well clear —which is different than the subjective "well clear" in 14 CFR Part 91, §91.111 and §91.113—is an event in which a UAS is in close proximity with another aircraft such that the following three conditions are concurrently true:

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, each of which will be described in detail in this section. The asterisked parameters are thresholds and the non-asterisked variables are measured or projected values. The dashed objects are projections of the aircraft. This schematic illustrates an encounter between a UAS flying level heading east and a manned aircraft flying level heading west.

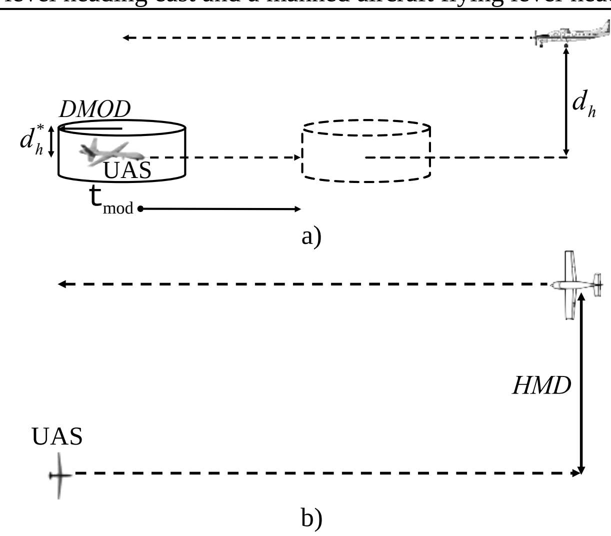


Figure 1. Schematic of parameters used to define loss of DAA well-clear (not drawn to scale): a) side view, and b) top view

1. Current Vertical Distance (d_h)

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

2. Horizontal Miss Distance (HMD)

The DWC definition also has a spatial metric in the horizontal dimension known as horizontal miss distance (*HMD*), which is defined as the projected separation in the horizontal dimension at predicted closest point of approach (CPA) using linear (constant velocity) extrapolation:

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

where

$$\begin{aligned} &d_x = x_2 - x_1 \quad \text{(horizontal separation in x-dimension)} \\ &d_y = y_2 - y_1 \quad \text{(horizontal separation in y-dimension)} \\ &v_{rx} = \dot{x}_2 - \dot{x}_1 \quad \text{(relative horizontal velocity in x-dimension)} \\ &v_{ry} = \dot{y}_2 - \dot{y}_1 \quad \text{(relative horizontal velocity in y-dimension)} \\ &t_{CPA} = -\frac{d_x v_{rx} + d_y v_{ry}}{v_{rx}^2 + v_{ry}^2} \end{aligned} \tag{1}$$

Note that t_{CPA} is positive when aircraft are converging

In the example illustrated in Figure 1 and described in the paragraph above it, HMD is the cross-track distance between the UAS and the manned aircraft because the former is flying due east while the latter is flying due west.

3. Modified Tau (τ_{mod})

The DWC definition also has a temporal separation metric known as "modified tau" or τ_{mod} that estimates the time to CPA between two aircraft. Modified tau is adopted from the collision detection logic of TCAS II[6] 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:

$$\begin{aligned} &\tau = -r / \dot{r} \\ &\text{where} \\ &r = \sqrt{r_{xy}^2 + d_h^2} \\ &r_{xy} = \sqrt{d_x^2 + d_y^2} \end{aligned} \tag{2}$$

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,[6] 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 are flying at approximately the same speed, on the same heading, offset by a small distance). In such a situation, the calculated tau value does not assure adequate separation because a sudden trajectory change that increases the closure rate (e.g., a turn) may cause loss of DWC. 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 uses a parameter known as "distance modification" (*DMOD*) to provide a minimum threat range boundary encircling the UAS. Modified tau (τ_{mod}) is defined as follows using horizontal range and horizontal range rate and measured in seconds:

$$
\tau_{\mathrm{mod}} = \begin{cases} 0 & \text{when } r_{xy} \le DMOD \\ -\dfrac{(r_{xy}{}^2 - DMOD^2)}{r_{xy}\dot{r}_{xy}} & \text{when } r_{xy} > DMOD \text{ and } \dot{r}_{xy} < 0 \\ \infty & \text{when } r_{xy} > DMOD \text{ and } \dot{r}_{xy} \ge 0 \end{cases} \tag{3}
$$

where $DMOD$ is a constant, and

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

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

Note that τ_{mod} is positive when aircraft are converging

B. Near Mid-Air Collision (NMAC)

An NMAC is defined as an event in which two aircraft are within 500 feet horizontally and 100 feet vertically of each other:[6]

1. $r_{xy} < r_{xy}^*$ where $r_{xy}^* = 500$ ft
2. $d_h \le d_h^*$ where $d_h^* = 100$ ft

III. Design of Experiment

A. Problem Statement

This experiment aimed to determine what criteria should be included in an equation that would define when vertical maneuvers should be allowed and when they should be suppressed for DAA systems performing well clear recovery. The initial hypothesis from discussion in SC-228 was that vertical maneuvers should be suppressed when vertical rate error exceeded some threshold value, initially set to 200 fpm. Preliminary work[8] focused on determining the effect of differing vertical rate error thresholds on the severity of a loss of DAA well clear. Results showed that vertical rate error alone was not a reliable indicator for when vertical well clear recovery (WCR) maneuvers should be allowed or suppressed. This paper summarizes the follow-on work that spurred SC-228 to develop the equation currently in the MOPS. This follow on work determined that, in addition to the vertical rate error present in a sensor, the climb and descent rate available to a UAS during WCR maneuvers could influence the severity of a loss of DAA well clear.

B. Simulation Platform

This study used a fast-time simulation with a generic resolver developed at NASA as a DAA system.[9] The simulation includes a model for selecting a maneuver from the guidance options offered and a model for pilot delays associated with evaluating and executing maneuvers in this domain. Aircraft were modeled using a kinematic trajectory generator that accepts aircraft performance constraints and produces trajectories that satisfy those constraints.

The maneuver itself was chosen by a part of the guidance algorithm, which used in this simulation as a proxy for the decision pilots would make when presented with vertical and horizontal DAA WCR guidance. This algorithm would select a vertical or a horizontal maneuver based on maximizing the predicted minimum separation, then send that maneuver to the UAS. The vehicle had a simple pilot-delay module that adds 6 seconds of delay before executing a maneuver. These delays were based on some unpublished, internal analysis performed on data from human-in-the-loop testing done in a previous study.[10] If the maneuver guidance was changed during the delay, a new maneuver would be chosen while the UAS continued executing any previous guidance. The delay would then be added again before beginning the new maneuver.

C. Sensor Model

Sensor errors were simulated based on a sensor model and fusion tracker developed by Honeywell and provided to NASA under contract*. This model was further tuned to match data from one of the flight tests performed previously in the course of the overall UAS research.[11] It added "noise" to the UAS's current position and speed (both vertical and horizontal), as well as the intruder's detected position and speeds. The only sensor model used in this test was the air-to-air radar, as the intruders were all non-cooperative. This radar also had field-of-regard limits that were based on the actual radar used in NASA flight testing. In this case, those limits are +/- 110 degrees for azimuth and +/- 15 degrees for elevation. More information on this sensor and tracker is provided in Ref. 12.

D. Encounter Sets

A series of pairwise encounters between a single UAS and a non-cooperative VFR aircraft was simulated in two mirrored groups of 54,000 encounters each. The first group allowed the DAA system and pilot model to select and fly vertical maneuvers to regain well clear when the DAA system determined that vertical maneuvers were the preferred solution. The second group of encounters forced the guidance algorithm to use only a horizontal maneuver to regain well clear. This allowed for a clear comparison between identical encounters in which a vertical maneuver was selected versus suppressed.

Each encounter consisted of a UAS and a non-cooperative VFR aircraft, referred to as an "intruder." The UAS began the encounter flying north at 9000 feet at a speed of either 50 or 200 knots. These speeds were based on anticipated airspeeds from the MOPS for UAS operating below 10000 feet mean sea level. The intruder's airspeed was either 70 or 170 knots. The upper intruder airspeed was taken from the MOPS as a nominal high airspeed for non-cooperative VFR aircraft below 10000 feet mean sea level, while the lower airspeed was chosen to represent very slow, non-cooperative fixed wing aircraft that could potentially operate at these altitudes. The intruder crossed the UAS's path at one of nine horizontal locations and five vertical distances with the intruder's heading angles varying from 0 degrees (north) to 180 degrees (south) in 45-degree steps. The crossing point was set to 70 seconds from the start of the simulation. The actual starting location of the intruder and the unmitigated closest point of approach was set by the simulation to meet each defined crossing point. This allowed a variety of intruder geometries to be tested. Further, the UAS's maximum turn rate, climb rate, and descent rate were varied independently, to determine which UAS performance parameters, if any, were primary factors in determining whether vertical resolutions produced more separation than horizontal maneuvers. The UAS was only permitted to maneuver after it received well clear recovery guidance from the DAA algorithm. The intruder did not maneuver in this simulation.

UAS performance parameters—airspeed, vertical rate, turn rate—as well as ranges of intruder states and encounter geometries are documented in the full encounter matrix in Table 1.

The experiment was designed to allow a direct comparison between the two sets of encounters (with vertical maneuvers allowed and with vertical maneuvers suppressed) because the errors seen by the guidance algorithm would be the same for encounters with the same initial conditions, and would only begin diverging when the UAS began its well clear recovery maneuver. This allowed the simulation tests to be broken into the two sets of 54,000 encounters discussed earlier. The trade-off for using this method was that a study of the effects of heading angles and similar parameters would be out of scope. For this simulation, every encounter that had the same initial states would see the same error distribution up until well clear recovery (WCR) was triggered and the UAS began maneuvering, regardless of the UAS's maneuver performance. Consideration was given to utilizing multiple simulation runs with differing noise parameters or random seeds, but such work was deemed out of scope for this study.

* The Honeywell DAA tracker is a sub-TRL6 tracker that is in its own iterative development cycle. This is one instantiation of the tracker with expected improvements in later versions to meet the developing DAA requirements and help with better alerting and guidance performance.

Table 1. Encounter matrix with 54,000 encounters. Full matrix was run twice: one test set allowed vertical maneuvers to regain well clear while the other test set did not. In all encounters, UAS were initialized flying level at 9000 feet heading due north. Each intruder was initialized 70 seconds before a defined crossing point. The UAS only maneuvered when it received Well Clear Recovery guidance from the DAA system.

Parameter Type	# Values	Values
UAS ground speed	2	50, 200 kts
Intruder ground speed	2	70, 170 kts
Intruder heading	5	0, 45, 90, 135, 180 deg
Intruder vertical speed	5	-2000, -1000, 0, 1000, 2000 ft/min
UAS trial plan maneuver turn rate	2	1.5, 3 deg/sec
UAS trial plan climb/descent rate	6	(500/500), (1000/1000), (1500/1500), (2000/2000), (500/2000), (2000/500) ft/min
Horizontal intruder trajectory shifting	9	0 nmi: (x,y) = (0,0) 0.2 nmi: (x,y) = (0.2, 0), (-0.2, 0), (0, 0.2), (0, -0.2) 0.5 nmi: (x,y) = (0.5, 0), (-0.5, 0), (0, 0.5), (0, -0.5)
Vertical intruder trajectory shifting	5	-400, -200, 0, 200, 400 ft

E. Performance Metrics

The primary metric was the Severity of Loss of DAA Well Clear (SLoWC), which is a measure of the minimum separation during an encounter. This metric was developed for the DAA MOPS. It estimates penetration into the DAA well-clear zone, and it accounts for vertical and horizontal separation. More details are given in Appendix B. The resulting SLoWC ranges from 0% to 100%, with 0% indicating Well Clear and 100% representing zero horizontal and vertical separation, that is, a collision. As an example, for a head-on, co-altitude encounter, moving from a horizontal miss distance of 4000 feet to 3000 feet increases the SLoWC by roughly 23%, while moving from 1000 feet to a horizontal miss distance of 0 feet increases the SLoWC by about 26%. The minimum value of SLoWC at which an NMAC can occur is around 70% and is dependent on the encounter geometry.

Another metric that is not explicitly measured but is a major factor in the results is the number of NMACs (as defined in Section IIB). When an NMAC occurs, there is a risk of a collision. The goal of Well Clear Recovery is to regain well clear separation and avoid an NMAC.

The analysis presented in this paper begins with the encounters where a vertical maneuver was chosen (in the data sets in which they were allowed). Those could be compared to the encounters with identical initial conditions in the data set where only horizontal maneuvers were allowed, as every encounter geometry tested was present in both sets. These pairs of encounters were checked to see if both the vertical and horizontal maneuvers began at the same time. Those encounter geometries with both a horizontal maneuver and a vertical maneuver at the same simulation time step were the only ones included in the primary analysis. This parity was seen as the fairest way of examining the effect of allowing (not requiring) vertical maneuvers, and assured that the initial horizontal and vertical maneuvers had the same estimated time to the closest point of approach (CPA) when the maneuvers were initiated. Otherwise there was the potential that one of the maneuvers would start significantly closer to the CPA, resulting in an inflated SLoWC. To eliminate these guidance changes, one would need to reduce sensor noise or improve smoothing without sacrificing the speed at which the algorithm reports unexpected intruder maneuvers—track accuracy, smoothness and processing times are tradeoffs of the tracker design. Note that DAA MOPS only have requirements on track accuracy and processing time. There are further tradeoffs in radar system design, with additional complications due to the frame of reference. For these air-to-air radars, an intruder's vertical position and rate must be determined by relative altitude estimation based on an elevation angle. Comparisons of these tradeoffs are out of scope for this study.

IV. Results

The first subsection below illustrates the vertical-rate error that was present in the simulation at the moment WCR guidance was triggered. This is to provide some context for the separations presented later in the results. The second subsection discusses the maximum SLoWC observed during a WCR maneuver for two different UAS performance levels.

A. Vertical-Rate Error

Figure 2 illustrates the vertical-rate error from the air-to-air radar and tracker model at the point when WCR guidance was triggered. Comparing this error to the loss of well clear definition's vertical separation threshold of 450 feet and a nominal time from WCR guidance to minimum separation of 40 seconds helps frame the difficulty accounting for this error during WCR. The range of these errors is one of the reasons early work in this area focused on when and how often to suppress vertical WCR maneuver guidance.

This vertical-rate error is not as problematic when dealing with cooperative intruders, as they are expected to be equipped with both a Mode C or Mode S transponder, and ADS-B.

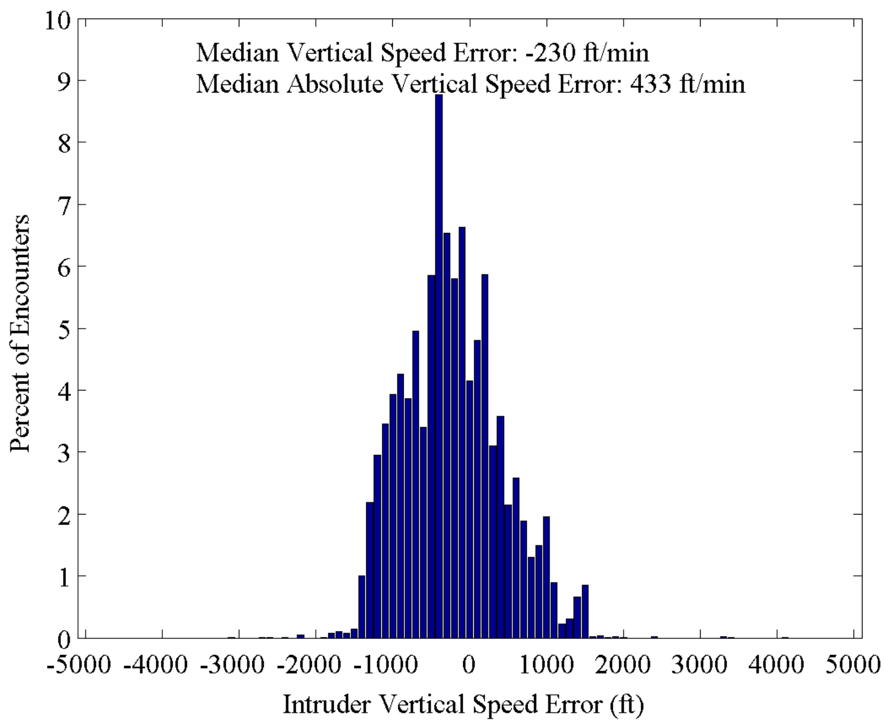


Figure 2. Vertical rate error from the radar and tracker at the time when the UAS began maneuvering to regain well clear.

B. Maximum Severity of Loss of DAA Well Clear

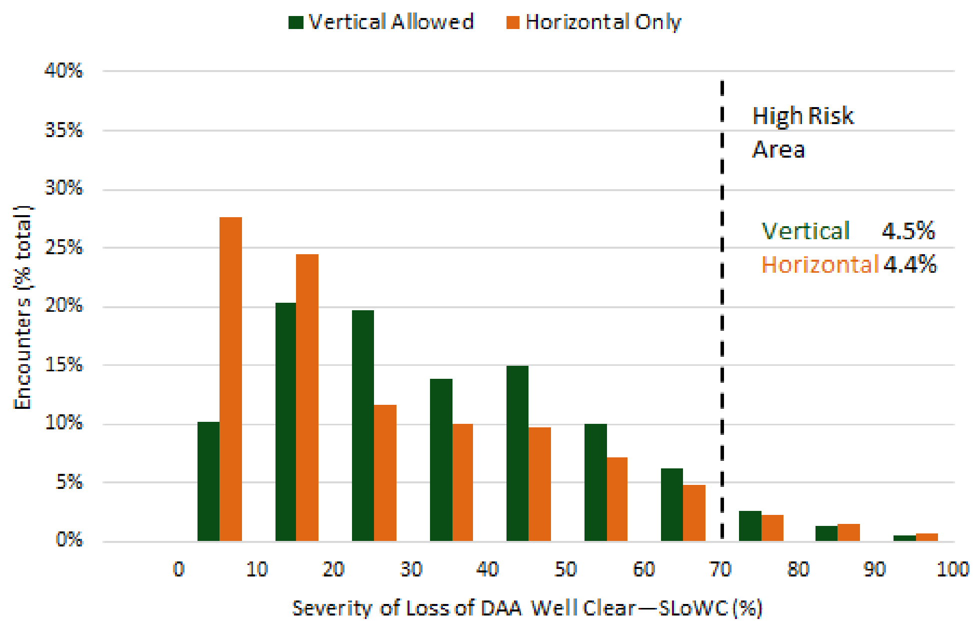
Figure 3 shows a comparison between the maximum Severity of Loss of DAA Well Clear (SLoWC) for the scenario where vertical maneuvers were allowed and chosen, and the scenario where only horizontal maneuvers were permitted, as described in Section IIID. Figure 3a) shows the percentage of encounters with certain SLoWC values, in bins of 10, for vertical and horizontal maneuvers for a UAS that could climb and descend at 2000 fpm. Figure 3b) shows the same results for a UAS that can only climb and descend at 500 fpm. For both of these figures, it is desirable to have taller bars to the left, as that corresponds to more encounters with a low SLoWC (more minimum separation). In these results, it can be seen that both the 2000-fpm and 500-fpm UAS have more horizontal encounters below a SLoWC of 20%, while there are more vertical encounters above a SLoWC value of 30%. This corresponds to an overall observation that horizontal maneuvers, on average, produced a lower value of SLoWC than vertical maneuvers. In other words, there was more net separation when horizontal maneuvers were employed in encounters where vertical maneuvers were preferred. For perspective, the median difference in SLoWC between horizontal and vertical maneuvers for the 2000-fpm UAS was 11%. An 11% difference in SLoWC corresponds to a distance of roughly 50 feet vertically for a head-on, co-altitude encounter with a horizontal CPA of zero. As the vertical or horizontal CPA increases, the vertical separation represented by that difference in SLoWC will also slightly increase. An 11% difference in SLoWC for a head-on, co-altitude encounter also corresponds to a difference in horizontal separation of 500 for low horizontal CPA values, and roughly 800 feet for higher horizontal CPA values. For the UAS that was limited to climb and descent rates of 500 fpm, the difference in median SLoWC was 13%.

There is also a slight difference in the percentage of encounters that are over the line representing a SLoWC value of 70%. This value marks the threshold of a high-risk area, as NMACs are possible above this value. The actual SLoWC of an NMAC will be dependent on the individual encounter geometry. The 2000-fpm UAS showed almost no difference between the number of encounters that had high-risk SLoWC values when vertical or horizontal maneuvers were used. For the 500-fpm UAS, however, horizontal maneuvers produced a lower percentage of encounters with SLoWC values over 70% than vertical maneuvers. A preliminary investigation into some of the effects of sensor errors[8] also revealed that lower sensor errors combined with UAS with high climb and descent rates had fewer encounters with high-risk SLoWCs when they employ vertical maneuvers than they did when they were forced to use horizontal maneuvers. This led to the hypothesis that higher performance UAS should be allowed to use vertical maneuvers in some cases, even though vertical maneuvers have a higher average SLoWC. Further analysis also suggests that as vertical-rate error decreases, higher-performance UAS are likely to experience fewer encounters with SLoWC over 70% if they can use vertical maneuvers.

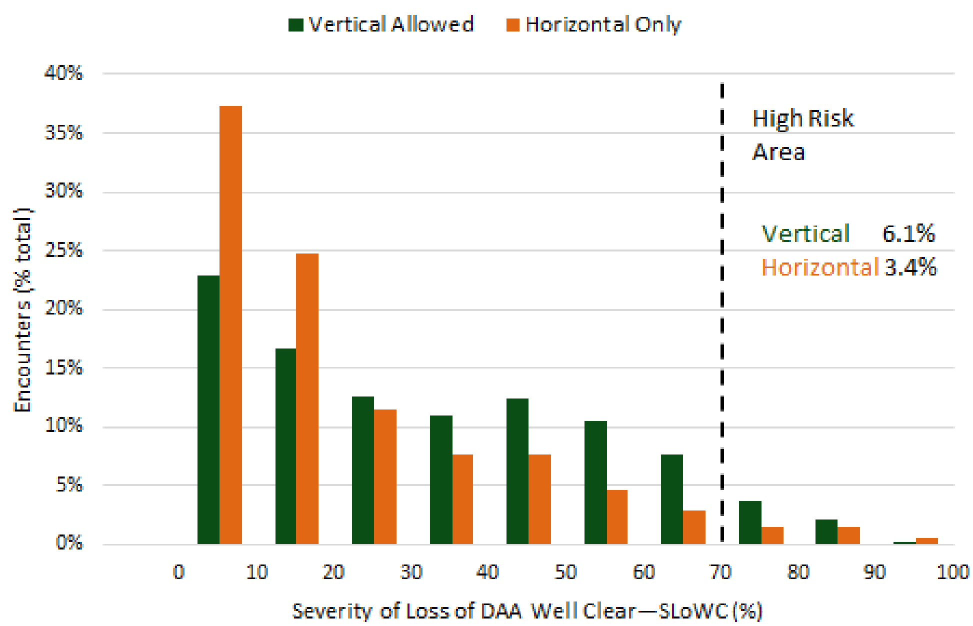
Though this is not explicitly in the figure, it should be noted that the number of encounters where vertical maneuvers were preferred by the generic algorithm discussed in Section IIIB is higher for UAS with high climb and descent performance. In the case of the UAS that could climb and descend at 2000 fpm, vertical WCR maneuvers were preferred in 75% of the total encounters. For the UAS that was restricted to climb and descent rates of 500 fpm, vertical maneuvers were preferred in only 30% of the total encounters. The results presented in this subsection focused on the encounters where vertical maneuvers were preferred. This was to help answer the question of whether or not vertical maneuvers should be suppressed, and if not, when should they be allowed.

These results were part of the data set that led to the adoption of the equation given in Appendix A. There was a general trend in all of the data that showed UAS with higher vertical rate performance available for WCR maneuvers had less difference between the SLoWC of horizontal and vertical maneuvers than vehicles with lower performance. There was also a larger difference between vertical and horizontal maneuvers when vertical-rate error was larger. This equation allows vertical maneuvers when the UAS can reach vertical rates that exceed the projected errors associated with the intruder. This will ensure that vertical maneuvers are only offered when they are safe, and will scale with technology, as improved air-to-air radar performance will allow vertical maneuvers to be utilized for WCR more often.

These results led to a discussion about potential cases when vertical maneuvers should be allowed. The idea of relying upon a fixed sensor-error threshold to determine when vertical maneuvers should be allowed did not fit with the data, particularly when considering the chance of high-risk encounters. SC-228 eventually came to a consensus that UAS vertical rate performance should be considered in addition to sensor error, and that the correct approach would be to compare the performance of the UAS with the intruder's potential position. This would allow UAS to use vertical maneuvers when their performance levels allowed them to avoid the intruder's potential position, based on the intruder's currently estimated state and the sensor errors. The equation that came out of that SC-228 discussion is given in Appendix A.



(a)



(b)

Figure 3. Severity of Loss of DAA Well Clear for UAS maximum vertical rate of a) 2000 fpm and b) 500 fpm. Horizontal maneuvers had lower SLoWC on average for both the 2000 fpm and 500-fpm UAS. The 500-fpm UAS had fewer encounters with high risk SLoWC (over 70) when using horizontal maneuvers. There was no change in the number of high risk SLoWC encounters when horizontal maneuvers were used for the 2000-fpm UAS.

C. Direct Comparison between Horizontal and Vertical Maneuvers

Figure 4 shows how SLoWC changes for an encounter when vertical maneuvers are suppressed. Similar to the previous chart, for the data set that allowed vertical maneuvers, each encounter where a vertical maneuver was chosen was stored. From there, the identical encounter from the data set with only horizontal maneuvers was stored. If the maneuvers from each data set were executed at the same time, the difference between the resulting SLoWC values was stored. These paired encounters are identical up until the point the UAS begins maneuvering. In effect, each data point represents the change in SLoWC for an individual encounter when a horizontal maneuver is used in place of a vertical maneuver. Positive values indicate a decrease in the SLoWC metric (more separation) when a horizontal maneuver is used instead of a vertical maneuver. Negative numbers denote an increase in SLoWC (less separation) when a horizontal maneuver is used instead of a vertical maneuver. The vertical dashed line in the center is simply to separate the areas where vertical maneuvers had more separation and horizontal maneuvers had more separation. As implied earlier, the generic DAA system preferred a vertical maneuver in each of these encounters.

The overall trend shows that, on average, SLoWC was lower when horizontal maneuvers were employed, regardless of vertical rate performance. This is consistent with results in Section IVB. Comparing between the results for the 500-fpm and 2000-fpm UAS, the data also show that the 500-fpm UAS had a higher percentage of encounters where a horizontal maneuver had a lower SLoWC by 30% or more (the 500-fpm UAS data are the yellow bars). The 2000-fpm UAS (the blue bars) had a higher percentage of encounters where the vertical maneuver had a lower SLoWC by 20% or more. These results were expected, as a UAS with higher climb and descent rates available when doing vertical maneuvers should be able to gain more vertical separation than a UAS with poor vertical acceleration over the same amount of time.

What was not expected, however, was that the overall percentage of encounters where vertical maneuvers had a lower SLoWC than horizontal maneuvers would be similar across all UAS performance levels. Data show that, for 38% of the encounters for the 2000-fpm UAS, the vertical maneuver had a lower SLoWC than the horizontal maneuver. For the 500-fpm UAS that number was 39%. There were a few more UAS performance levels tested in preliminary work, and they also had a similar percentage of encounters where vertical maneuvers had less separation. Some of that could be attributed to chance, as there is always a likelihood that a vertical maneuver will produce more separation than a horizontal maneuver, even with large vertical rate uncertainty. However, the fact that the percentage of encounters where this was true was seemingly insensitive to the vertical performance of the UAS raised a question of whether there could be another important factor influencing the data. It is possible that some encounter geometries may be more difficult to resolve with horizontal maneuvers, even in the presence of large intruder vertical rate errors. One type of encounter was found where this seems to be true, and it is discussed in Section VB, below. It is possible that there are more encounter geometries, but a full analysis of encounter geometries would require a different analysis approach and was out of scope for this work.

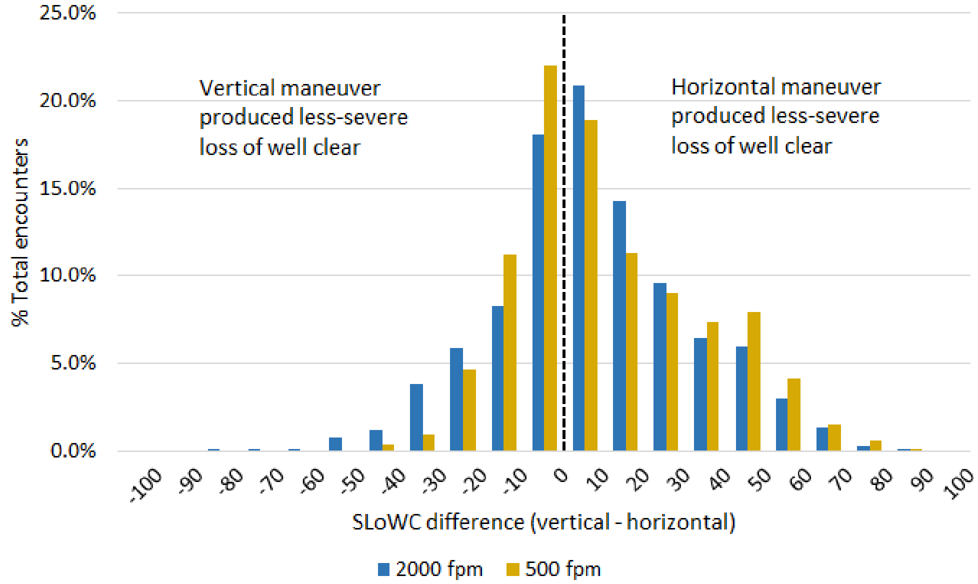


Figure 4. Change in SLoWC when a horizontal maneuver is forced compared to the SLoWC when a vertical maneuver was used. On average, encounters have lower SLoWC when horizontal maneuvers are used in place of vertical. This change in SLoWC is more pronounced for the 500-fpm UAS. However, the percentage of total encounters where vertical maneuvers have lower SLoWC is roughly the same for both 2000-fpm and 500-fpm UAS.

V. Discussion

A. Severity of Loss of DAA Well Clear

There are multiple potential causes for why suppressing vertical maneuvers would lead to more severe losses of well clear when attempting to regain DWC. One potential reason would be conflict geometries that are difficult to resolve with horizontal maneuvers. An example of this type of encounter is in the next section. It is also possible that it is more difficult to recover from a poor initial maneuver choice when the only option is a reversal, due to the other dimension being suppressed. The difficulty is predicting when it would be worth attempting a vertical resolution. Exploring the encounter set in more detail was out of scope for this paper, but could lead to better understanding of when vertical maneuvers are more likely to result in increased separation and reduced NMAC risk. However, even with that knowledge, it is the author's opinion that it would be difficult for algorithms that are only using state-based trajectory predictions and trajectory smoothing to reliably determine when vertical resolutions could be beneficial, outside of using an equation such as the one in Appendix A. To further reduce the number of severe losses of well clear using vertical maneuvers will likely require adjustments on the algorithmic side, or waiting for sensor errors to be drastically reduced. For algorithms, it is possible that adding tools that can utilize trajectory prediction error distributions, or heuristics that can help the algorithm determine when and how to respond to large shifts in vertical rate predictions, could produce systems that have a lower NMAC risk while allowing more vertical maneuvers. However, such algorithmic design and testing is out of scope for this work.

The current requirements in the MOPS allow vertical maneuvers when the vertical rate achievable by the UAS compares favorably with the vertical-rate error and position of the intruder. That seems adequate for current systems, and could be implemented with a generic DAA algorithm as long as there is knowledge of the sensor system and its characteristic errors. However, data gathered for this study showed there are enough encounters in which the suppression of vertical maneuvers resulted in lower separation to warrant further study, and that the average minimum separation achieved should not be the sole indicator for determining the best maneuver for preventing NMACs in a future system.

B. Horizontal Maneuver Ambiguity

This section highlights a type of encounter where vertical-rate error can strongly affect the separation obtained during a vertical maneuver. This is due to the vertical-rate error changing the predicted co-altitude point during a crossing conflict with an intruder that is changing altitude. These cases do not necessarily lead to a dangerous maneuver or an NMAC, but they can make those events more likely if the wrong turn direction is chosen.

A few of these cases appeared in the data, but the encounter matrix used for this study had a limited number of these encounters. Additionally, the trajectories from the cases where an incorrect initial turn direction led to a turn reversal were complicated, as the guidance algorithm was trying to find the correct trajectory through some large variations in sensor noise. Therefore, to highlight the class of encounter, rather than the way a specific algorithm attempted to recover from an incorrect initial turn, this paper will cover these encounters with a general example.

Figure 5 shows an example encounter where vertical-rate error has a large effect on the suitability of a horizontal maneuver as well as vertical. In this example, there is an intruder that is estimated at 1300 feet above the UAS, descending at a predicted rate of 1500 fpm, and is projected to pass above the UAS if no action is taken. The horizontal closure rate is 135 knots, and the vertical-rate error is +/- 1000 fpm. Further assume there are 45 seconds until the horizontal CPA.

In this example, the ground speed of the intruder is the same for all descent rates. The exact ground speeds and encounter angle are not specified, as the specific encounter geometry is not what is being highlighted. The encounter is a crossing conflict, though the heading difference does not have to be exactly 90 degrees. If the descent rate is 1500 fpm, as shown with the blue line, the intruder will reach a horizontal separation of zero in 45 seconds with 175 feet of vertical separation.

If the intruder is descending at 2500 fpm, as shown with the grey line, it will reach co-altitude in just over 31 seconds with over 3000 feet of horizontal separation, and will reach zero horizontal separation with 575 feet of vertical separation. Therefore, if the intruder is descending faster than predicted, the UAS should turn away from the intruder. If the intruder is descending at 500 fpm, as shown with the orange line, it would not reach co-altitude for 156 seconds, and would cross zero horizontal separation with 925 feet of vertical separation. Turning towards the intruder would be the correct option in this case, though the UAS might not need to maneuver at all to avoid a loss of well clear.

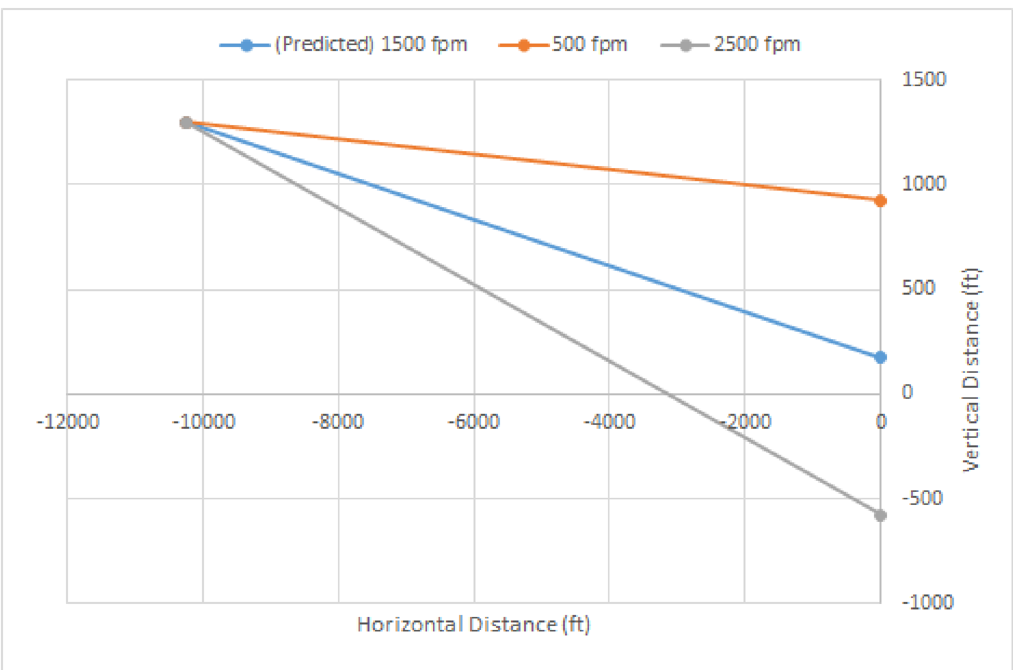


Figure 5. Intruder descent profile in terms of horizontal and vertical distance from the UAS. This shows the progression of vertical separation based on horizontal separation between UAS and an intruder up until the horizontal separation is zero. Each line represents a possible intruder descent rate based on an error range of +/- 1000 fpm and a predicted intruder descent rate of 1500 fpm.

Encounters like this could make vertical maneuvers preferable even if the predicted separation is not as high as it is for horizontal maneuvers and the level of vertical-rate error is large. In the above encounter, if the UAS can climb above the altitude at which the intruder would be in 45 seconds (intruder was descending at the minimum rate), an NMAC could be prevented, regardless of the intruder's actual descent rate. However, a horizontal turn, even though the potential separation achieved might be higher, could result in a more dangerous scenario if the UAS chooses the wrong initial turn direction. In the case of a turn towards the intruder with the intruder descending faster than predicted, the UAS could find itself in a similar situation to the initial encounter, only with significantly less time until CPA. With a turn away from an intruder that is descending more slowly than predicted, the UAS could put itself into a "chase scenario" where the UAS will need to either outrun the intruder or rely on the intruder to make a maneuver of its own. This is further complicated by the UAS radar's field of regard. If the UAS turns in front of a non-cooperative intruder, there is a risk that it will lose sight of the intruder, depending on the conflict geometry and field-of-regard value.

This highlights the field of regard as a potential complication for horizontal maneuvers. This could become an issue depending on encounter geometry, relative ground speeds, and the horizontal maneuver selected by the UAS. However, an exploration of this was out of scope for the current work.

These encounters could also benefit from guidance algorithms that use risk-based or heuristic approaches to mitigating sensor errors, rather than a more traditional approach that is built on a primary trajectory prediction. This would likely become less important as air-to-air radar vertical-rate errors decrease, but for current error levels it can be difficult to make the safest decision based only on a predicted trajectory and an error distribution.

VI. Conclusions

This study examined two sets of 54,000 encounters in which the UAS was forced into a predicted loss of DAA well clear. In one set, the UAS was allowed to choose vertical maneuvers for WCR guidance; in the other set, the UAS was restricted to horizontal guidance. Results of the study showed that the average separation was higher when vertical maneuvers were suppressed, in terms of the "severity of loss of DAA well clear" metric. However, it was noted that a UAS' climb and descent rate available for WCR maneuvers influenced the percentage of encounters that were high risk (potential NMAC). Specifically, the percentage of high-risk encounters when using vertical maneuvers decreased as the UAS climb and descent performance increased, and the sensor vertical rate errors decreased. Accordingly, it is suggested that UAS should be allowed to maneuver vertically when their vertical performance is high enough to avoid the potential positions of the intruder (based on the intruder's estimated position, vertical rate, and the characteristic vertical rate error of the sensor on the UAS). This conclusion led to the equation in the MOPS, which is shown in Appendix A.

Additionally, in roughly 38% of the encounters, the severity of an encounter increased when a horizontal maneuver was used in place of a vertical maneuver. This percentage was seemingly independent of UAS climb and descent performance, and led to a preliminary investigation of other potential factors that could make vertical maneuvers preferable to horizontal maneuvers, even with large levels of vertical rate error. One potential factor was certain conflict geometries that are intrinsically difficult to safely resolve with horizontal maneuvers, due in large part to the effect of vertical-rate error. One such case highlighted in this paper is a crossing conflict with an intruder that is changing altitude, where the vertical-rate error can have a large effect on the left/right turn decision. In some of these cases, a vertical maneuver might not offer as much separation on average but potentially could have less risk of an NMAC in the worst case.

Overall, the results support the equation developed by RTCA Special Committee 228 for the DAA MOPS as a solution that is implementable now. This equation allows for vertical maneuvers if the UAS's performance exceeds the non-cooperative intruder's vertical-rate error, estimated vertical position and estimated vertical rate. However, for future solutions it is recommended that crossing conflicts with a descending or climbing intruder be investigated, as well as the stability of a maneuver (likelihood of a second maneuver being required) and NMAC risk. There is also a potential need to improve horizontal guidance algorithms for difficult encounters, such as through heuristics or risk-based methods, to more intelligently chose a target heading when large errors make it difficult for a traditional trajectory prediction to find a stable solution.

Appendix A: Equation for Suppressing Vertical Maneuvers

This is the equation from the MOPS. It is used to determine when to provide vertical maneuver guidance to regain well clear in relation to non-cooperative intruders. When the following inequality is true, vertical maneuver guidance must not be offered.

$$\frac{1}{2}\cdot\left(E_{\Delta\dot{h}}\cdot t_{CPA}+E_{\Delta h}\right)>\left|\left(\dot{h}_{own\_maneuver}-\dot{h}_{own}-\Delta\dot{h}_{tracker}\right)\cdot t_{CPA}-\Delta h_{tracker}\right| \tag{4}$$

where

$E_{\Delta\dot{h}}$ is the 95% threshold of the relative vertical velocity accuracy as estimated by the DAA tracker.

t_{CPA} is the estimated time to closest point of approach.

$E_{\Delta h}$ is the 95% metric threshold of the relative vertical position accuracy as estimated by the DAA tracker.

$\dot{h}_{own\_maneuver}$ is the planned vertical velocity of the maneuver that will be used by the UAS. By default, 500 feet per minute should be used as the minimum allowable performance unless the applicant specifies that a larger value is used by guidance to regain DWC. Different values may be used for climbs and descents, in which case the inequality above should be checked for each value.

$\dot{h}_{own}$ is the current vertical velocity of the UAS as estimated by the DAA tracker.

$\Delta\dot{h}_{tracker}$ is the current relative vertical velocity between the intruder and UAS as estimated by the DAA tracker. It is equal to the intruder's vertical velocity minus the UAS's vertical velocity.

$\Delta h_{tracker}$ is the current relative vertical position between the intruder and UAS as estimated by the DAA tracker. The relative vertical position is equal to the intruder's vertical position (altitude) minus the UAS's vertical position (altitude).

Appendix B: Severity of Loss of DAA Well Clear (SLoWC)

The value of Severity of Loss of DAA Well Clear (SLoWC) that is reported in the results section is the maximum SLoWC for each encounter. The value of SLoWC for each point of that encounter is determined by the following equation: This equation was developed for the SC-228 MOPS.

$$SLoWC=(1-RangePen\oplus HMDPen\oplus VertPen)\cdot 100\% \tag{5}$$

where the Fernandez-Gausti's squircle is defined as

$$x\oplus y\equiv\sqrt{x^2+(1-x^2)\cdot y^2} \tag{6}$$

The *RangePen* is defined as

$$RangePen=MIN\left(\frac{r}{S},\ 1\right) \tag{7}$$

Where S is a horizontal distance threshold defined by

$$S = MAX\left(DMOD,\ \frac{1}{2}\cdot\left(\sqrt{(\dot{r}\cdot\tau^*_{\text{mod}})^2 + 4\cdot DMOD^2} - \dot{r}\cdot\tau^*_{\text{mod}}\right)\right)$$
$$\text{where } DMOD = 4000 \text{ ft},\ \tau^*_{\text{mod}} = 35 \text{ sec},$$
$$r_i \equiv \text{horizontal range},$$
$$\dot{r}_i \equiv \text{horizontal range rate} \tag{8}$$

The *HMDPen* is defined as

$$HMDPen = MIN\left(\frac{HMD}{DMOD},\ 1\right)$$
$$\text{where}$$
$$HMD = \begin{cases} \sqrt{(d_x + v_{rx}t_{CPA})^2 + (d_y + v_{ry}t_{CPA})^2} & \text{for } t_{CPA} > 0 \\ r_{xy} & \text{for } t_{CPA} \le 0 \end{cases} \tag{9}$$

Note that the equation for HMD is different than in equation 1. This is because setting HMD to negative infinity when t_{cpa} is less than zero would result in *HMDPen* values of negative infinity, as well. The above definition ensures the value of *HMDPen* is continuous throughout the Loss of Well Clear.

The *VertPen* is defined as

$$VertPen = MIN\left(\frac{d_h}{H^*},\ 1\right)$$
$$\text{where } d_h = |h_1 - h_2|$$
$$\text{and } H^* = 450 \text{ ft} \tag{10}$$

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