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Interoperability of Horizontal and Vertical Resolution Advisories

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***Abstract*—To operate in civil airspace, unmanned aircraft systems (UAS) are expected to maintain safe separation from other aircraft. Self-separation and Collision Avoidance Systems (CAS) designed for unmanned aircraft are under development to meet this requirement. To maintain airspace safety, these systems must interoperate safely with CAS onboard manned aircraft. Whereas manned aircraft CAS such as TCAS and ACAS Xa issue vertical resolution advisories (RA) that may direct aircraft to climb or descend, new UAS systems may issue horizontal RAs that direct aircraft to turn left or right, potentially leaving UAS free to maneuver vertically during the collision avoidance timeframe. These vertical maneuvers may negatively interact with manned aircraft employing a vertical CAS, representing a potential safety risk. This paper summarizes a study conducted to determine the extent of this safety risk and whether the vertical dynamics of UAS should be constrained to ensure interoperability. Fast time simulations were conducted to determine the collision risk of encounters between an aircraft equipped with TCAS or ACAS Xa and a UAS equipped with ACAS Xu: a CAS developed for unmanned aircraft. A worst-case-scenario approach was taken in which the UAS altered its vertical rate towards the intended path of the manned aircraft during the collision avoidance timeframe. The results show that ACAS Xa was safer and more robust to the UAS's vertical maneuvers than TCAS. A vertical coordination scheme was also evaluated and was shown to reduce collision risk. These results will contribute to the drafting of interoperability recommendations for UAS collision avoidance and self-separation system behavior in encounters with manned aircraft.**

***Key Words*—Traffic Alert and Collision Avoidance System (TCAS), Airborne Collision Avoidance System (ACAS), sense and avoid (SAA), unmanned aircraft systems (UAS), aviation safety, self separation**

I. INTRODUCTION

To operate in civil airspace, unmanned aircraft systems (UAS) are expected to maintain safe separation from other aircraft [1]. New self-separation and Collision Avoidance Systems (CAS) designed for unmanned aircraft are under development to meet this requirement. To maintain airspace safety, these new systems must interoperate safely with CAS onboard manned aircraft. Therefore, the interactions of manned aircraft collision avoidance and unmanned aircraft collision avoidance and self-separation must be understood.

Many of the self-separation and collision avoidance systems under development for unmanned aircraft provide horizontal guidance, alerting UAS to turn left or right to avoid intruders. In contrast, both TCAS (Traffic Alert and Collision Avoidance System), the internationally-mandated CAS required onboard all large transport aircraft, and its planned successor ACAS Xa[1] (Airborne Collision Avoidance System X), issue only vertical resolution advisories (RA) such as *Climb* or *Descend*. Both TCAS and ACAS Xa issue RAs based in large part on the projected vertical trajectories of intruder aircraft. A UAS receiving only horizontal guidance would notionally be unconstrained in the vertical dimension, meaning it would be free to change its vertical rate at the same time it is directed to turn. Such changes to vertical rate could occur for a variety of reasons, including dynamic restrictions on the UAS (e.g., near its service ceiling, it may not be able to maintain its current climb rate and turn at the same time) or the actions of the UAS operator. If these changes to vertical rate occurred during the RA timeframe of an intruder equipped with TCAS or ACAS Xa, then the safety benefit provided by those systems could be degraded.

For example, consider an encounter between a TCAS-equipped manned aircraft and a UAS receiving horizontal guidance only. The TCAS aircraft is above the UAS and is descending towards it, while the UAS is climbing slowly near its service ceiling. As some point, TCAS issues an RA directing the manned aircraft to maintain its descent and cross altitudes with the UAS. At around the same time, the horizontal logic on the UAS directs it to turn. To comply, the UAS is forced to descend due to dynamic restrictions near its service ceiling. This creates a dangerous situation in which both aircraft are descending and the RA issued by TCAS will no longer resolve the encounter. This may cause an RA

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[1] ACAS Xa (a for *active coordination*) is the member of the ACAS X family of collision avoidance logics intended for aircraft currently carrying TCAS.

reversal on the TCAS aircraft and in some extreme cases a mid-air collision[2].

The purpose of this study is to investigate the robustness of TCAS and ACAS Xa to sudden changes in UAS vertical rate within the collision avoidance timeframe. While previous studies have confirmed the need for aircraft receiving vertical advisories to constrain their vertical maneuvers through coordination [2], this study intends to determine what vertical constraints or coordination may be necessary for aircraft receiving only horizontal advisories during encounters with vertical CAS-equipped aircraft. The investigation is divided into two questions:

1. Under what circumstances will the vertical maneuvers of a UAS receiving only horizontal guidance increase collision risk against an intruder aircraft receiving vertical collision avoidance guidance?
2. What is the safety benefit of vertical coordination in encounters between such aircraft? (Note that vertical coordination would be required if the UAS were being provided with vertical advisories.)

Coordination is the mechanism that prevents two CAS-equipped aircraft from taking the same action (e.g., both climbing or descending) during an encounter. If risk is elevated due to the unconstrained vertical maneuvers of a UAS receiving only horizontal guidance, then constraining its vertical maneuvers through coordination may mitigate that risk.

The results of this study will contribute to recommendations for interoperability between UAS collision avoidance and self-separation systems and manned collision avoidance systems. These recommendations will address the necessity of vertical coordination in these encounters as well as any constraints that should be placed on UAS vertical rate changes.

Although this work is focused on interactions between unmanned and manned aircraft, the results and recommendations of this study are applicable to any encounters in which one aircraft might unexpectedly maneuver vertically during the collision avoidance timeframe of a vertical CAS-equipped intruder. Encounters between transport category and low-performance General Aviation aircraft are another example of this type of encounter.

A. TCAS and ACAS X

TCAS[3] was initially developed in the United States during the 1970s and 1980s in response to a series of deadly mid-air collisions between United States civil aircraft [3]. Mandated internationally for large transport aircraft, TCAS has substantially reduced the risk of airborne collisions since its introduction [4].

TCAS alerting logic is based on linear extrapolation of intruder trajectories and a large set of heuristic rules. As the development of TCAS Versions 7 and 7.1 exemplified, modifying these rules is extremely difficult and time consuming. In light of this and to ensure safe and effective collision avoidance in the future airspace environment, in 2009, the Federal Aviation Administration TCAS Program Office began formal research on a next generation airborne collision avoidance system: ACAS X.

Whereas TCAS logic is based on linear extrapolation and heuristic rules, ACAS X logic is based on a dynamic model of aircraft movement and a computer optimized lookup table of collision avoidance actions. This design makes ACAS X substantially easier to adapt to specific aircraft, airspace procedures, and surveillance technologies [5]. ACAS X is a family of adaptations [6], two of which are relevant to this study: ACAS Xa and ACAS Xu.

ACAS Xa is being designed as a direct replacement for TCAS, with intent to provide improvements in safety and operational suitability. ACAS Xu is being designed for UAS, and as such it is optimized for the aerodynamic performance and surveillance systems characteristic of those platforms. ACAS Xu, unlike TCAS and ACAS Xa, is able to provide horizontal RA guidance. In this study of the interactions of vertical collision avoidance and a system providing UAS with horizontal guidance, ACAS Xu's horizontal logic fills the role of the system providing horizontal guidance. Note that ACAS Xu is also able to provide vertical RA guidance[4], but this analysis is focused solely on its horizontal logic.

Even though ACAS Xu is a collision avoidance system, the results of this study are applicable to any CAS or self-separation system providing guidance that may cause vertical maneuvers within the collision avoidance timeframe.

The next section of this document describes the encounters between aircraft equipped with TCAS, ACAS Xa, and ACAS Xu that were simulated to arrive at the results, which are laid out in Section III. Critical findings are highlighted among the results, which are synthesized into recommendations in the document's conclusion in Section IV.

II. METHODOLOGY

To answer the questions posed in the previous section, several million encounters between a UAS equipped with ACAS Xu and a manned aircraft equipped with TCAS or ACAS Xa were simulated in fast time. This modeling and simulation framework is the standard approach in the tuning and evaluation of collision avoidance systems [6], [7], [8]. These encounters were simulated under a range of variable parameters (see below), and the collision risk was estimated for each configuration of parameters.

[2] This study shows that the risk of collision in situations such as this depends in part on the horizontal guidance issued to the UAS.

[3] In this document, TCAS refers to TCAS II, known internationally as ACAS II (Airborne Collision Avoidance System).

[4] ACAS Xa uses the same set of vertical advisories as TCAS, whereas ACAS Xu's vertical logic uses a reduced set of advisories.

Encounters were generated from the Lincoln Laboratory Correlated Encounter Model (LLCEM) [9]. Constructed from radar data collected in United States airspace between 2007 and 2008, the LLCEM is a probability distribution of encounter parameters for aircraft receiving air traffic services. Two of these parameters are especially relevant to this study: aircraft vertical rate and relative horizontal and vertical position at the time of closest approach (TCA).

To capture the wide range of performance capabilities of real UAS, the maximum vertical rate of the simulated UAS was a variable with three discrete levels: ±1500, ±1000, or ±500 feet per minute (fpm). To capture the potential for sudden changes in vertical rate on real UAS, the vertical rate of the simulated UAS was increased or decreased by a prescribed amount when it received the first horizontal RA of an encounter. This approach was taken for two reasons. First, as previously described, vertical rate changes on a UAS can be expected to occur as a result of complying with horizontal guidance in some situations. Second, it was expected that ACAS Xu would issue horizontal RAs within or close to the collision avoidance timeframe of TCAS and ACAS Xa: when changes to UAS vertical rate have the highest potential to degrade safety.

The magnitude of the prescribed change to vertical rate was another variable and was a function of the UAS's maximum vertical rate (see Table I). The direction of the change in vertical rate was always towards the intended path of the manned aircraft[5], which was determined a priori by simulating the manned aircraft encountering an unequipped intruder (i.e., an intruder not receiving any CAS or self-separation guidance). Furthermore, although the simulated UAS was receiving horizontal guidance from ACAS Xu, that guidance was ignored, meaning the UAS did not turn in response to its RAs.

This methodology represents a worst-case scenario approach: not only does the UAS suddenly change its vertical rate towards the intended path of the manned aircraft, neither aircraft receives any safety benefit from ACAS Xu's logic. This approach was taken because it imposes the maximum stress on TCAS and ACAS Xa, whose performance in the real environment will likely equal or exceed the results of this study. In recognition of this, an identical set of encounters was simulated in which the UAS did turn in response to its horizontal guidance, the results of which are also included in this report.

A vertical coordination scheme was also evaluated to determine how much it would mitigate the collision risk introduced by the UAS's vertical rate changes. Coordination prevents two aircraft from taking the same action in their attempt to avoid one another. Aircraft equipped with TCAS or ACAS Xa employ *active coordination* against one another.

TABLE I. SUMMARY OF SIMULATION PARAMETERS

Parameter	***Manned Aircraft***	***Unmanned Aircraft***
CAS	TCAS II v7.1 or ACAS Xa	ACAS Xu Horizontal Logic
Vertical Rate Limit (fpm)	No limit beyond that of encounter model	±1500, ±1000, or ±500
Vertical rate change after horizontal RA (fpm)[a]	N/A	Vertical rate limit ±1500: 1500, 1000, 500, 250 or 0 Vertical rate limit ±1000: 1000, 500, 250, or 0 Vertical rate limit ±500: 500, 250, or 0
Surveillance	TCAS MOPS	Perfect (Errorless)
Coordination	None or vertical coordination scheme described above	
RA Response Delay	5 seconds initial, 3 seconds subsequent	

a. The vertical rate limits of the UAS always took precedence over vertical rate changes.

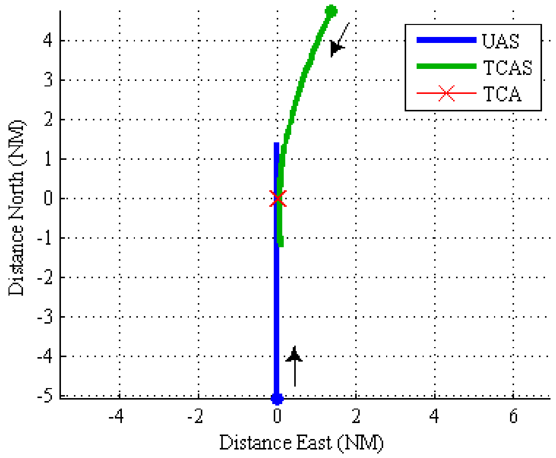
With active coordination, pairs of aircraft communicate the vertical sense of the RAs they issue, restricting the RAs available to the other aircraft to those of the opposite sense. In this study, *responsive coordination* was employed. With responsive coordination, only one aircraft is restricted by the other, with the UAS being restricted by the manned aircraft in this analysis. Furthermore, the vertical rates available to the UAS were restricted, not its RAs. Whenever the manned aircraft issued an RA, the UAS behaved as if it received a *Do not Climb* or *Do not Descend* command, whichever was complementary to the RA selected by the manned aircraft. To comply, this sometimes meant that the UAS was forced to level off. Furthermore, complying with this command superseded any vertical rate changes occurring after a horizontal RA was issued. This coordination scheme was studied previously in [10], which showed that it benefited safety over a no-coordination case.

The quality of the surveillance provided to the CAS onboard both aircraft was another simulation parameter. Surveillance quality affects a CAS or self-separation system's ability to accurately ascertain the current state of intruder aircraft, which in turn affects its alerting decisions. The manned aircraft was provided with active surveillance with noise parameters modeled after what is required for TCAS operation, as laid out in the TCAS Minimum Operational Performance Standards (MOPS) [11]. The UAS was provided with noiseless surveillance.

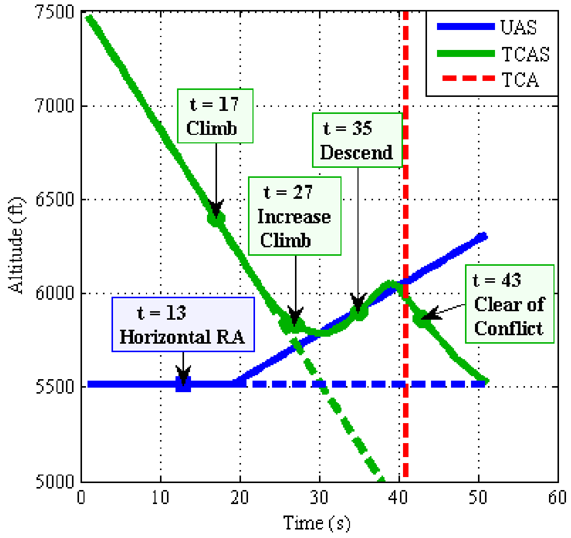
Finally, in keeping with standard practice in simulations of collision avoidance, both aircraft delayed their response to the initial RA in a sequence of advisories by 5 seconds and delayed their responses to subsequent RAs by 3 seconds. These delays also applied to the unmanned aircraft's vertical rate changes, both those that followed horizontal RAs and those caused by vertical coordination.

The parameters of this study are summarized in Table I.

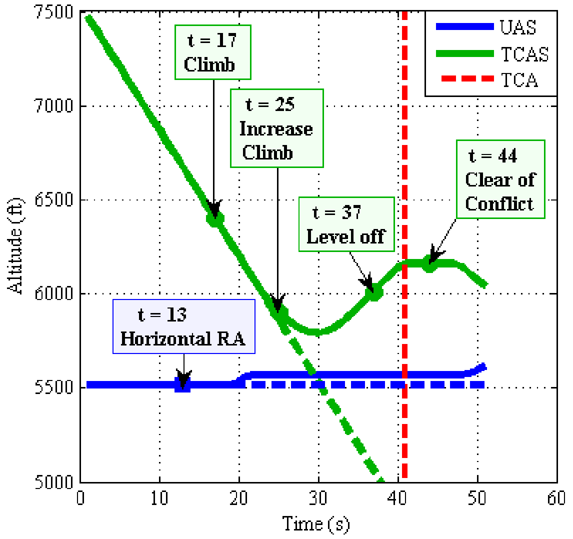
[5] For example, if in an encounter the manned aircraft intended to avoid the UAS by passing above it, then the UAS would increase its climb rate upon receiving its first horizontal RA.



(a) Horizontal profile



(b) Vertical profile without coordination



(c) Vertical profile with coordination

Figure 1. Example encounter between the UAS and a TCAS-equipped manned aircraft

Fig. 1 depicts an example encounter, included to illustrate the parameters of this analysis. In this encounter between the UAS and a TCAS-equipped manned aircraft, the vertical rate limit of the UAS is ±1500 fpm and its vertical rate change after horizontal RA is also 1500 fpm. Fig. 1a is the horizontal profile of this encounter, showing the UAS approaching the manned aircraft nearly head on.

Fig. 1b and 1c depict the altitudes and RAs issued by the two aircraft over time. Fig. 1b represents the case where responsive coordination is not in use and Fig. 1c represents the case where it is in use. In both figures, solid lines depict the trajectories of the two aircraft when they are receiving RAs and dashed lines depict their trajectories when they are not receiving RAs (the *nominal* case). At t = 13, the UAS receives a horizontal RA and in keeping with the worst-case assumption of this study, initiates a vertical maneuver towards the manned aircraft by increasing its climb rate to 1500 fpm after a 5 second delay. Also note in Fig. 1a that the UAS does not turn in response to the horizontal RA. The actions of the UAS in this encounter lead to a near mid-air collision (NMAC), which is defined to occur when the two aircraft come within 500 feet horizontally and 100 feet vertically of one another. With responsive coordination, the UAS responds to the *Climb* RA on the manned aircraft by leveling off, and the NMAC is avoided.

III. Results

A. *Performance Metrics*

The primary metric of this study was risk ratio, the standard safety metric in collision avoidance performance assessment, defined below. Also, because the vertical rate changes on the UAS occurred in response to its initial horizontal RA, the relative timing of the initial RAs issued by ACAS Xu, ACAS Xa, and TCAS was also tracked.

In this study, the numerator of risk ratio is the probability of NMAC given an encounter when both aircraft are receiving RAs, except for the baseline cases (see below), in which only the manned aircraft is receiving RAs. The denominator of risk ratio is the probability of NMAC given an encounter when neither aircraft is receiving RAs:

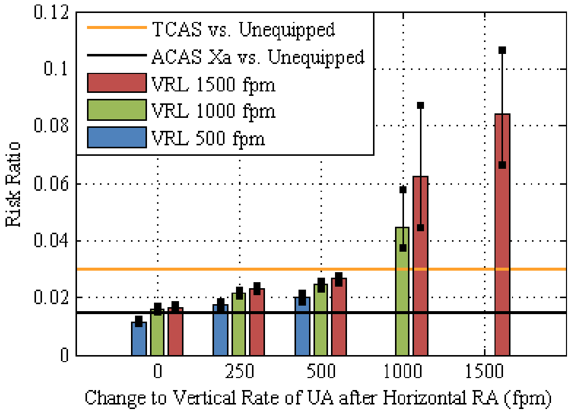
$$\text{Risk Ratio} = \frac{\text{P(NMAC | One or Both Aircraft Receiving RAs)}}{\text{P(NMAC | Neither Aircraft Receiving RAs)}} \quad (1)$$

Note that for the UAS, "receiving RAs" implies that it is changing its vertical rate in conjunction with its initial horizontal RA as described in Section II, regardless of whether or not it is turning in response to its RAs.

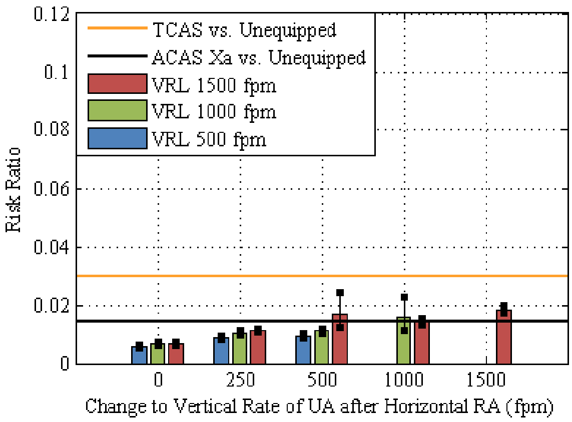
A risk ratio of 1 indicates that providing one or both aircraft with RA guidance has no effect on collision risk, whereas a risk ratio below 1 indicates a decrease in risk and a risk ratio above 1 indicates an increase in risk.

B. *Baselines*

To gauge the effect of UAS vertical maneuvers on safety, two safety baselines were established: one for TCAS and one for ACAS Xa. These baselines represented the risk ratio for

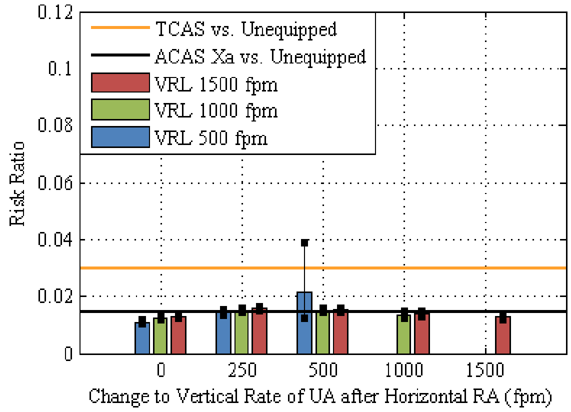


(a) TCAS on manned aircraft

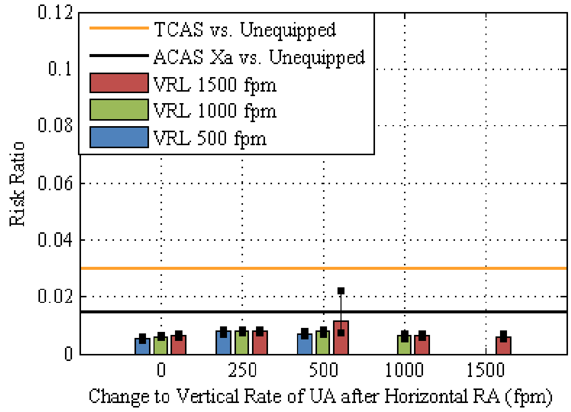


(b) ACAS Xa on manned aircraft

Figure 2. Risk ratio without coordination



(a) TCAS on manned aircraft



(b) ACAS Xa on manned aircraft

Figure 3. Risk ratio with coordination

encounters between one aircraft equipped with TCAS or ACAS Xa and another equipped with a Mode S transponder only and no RA guidance. No special vertical rate limits were imposed on either aircraft beyond those inherent to the LLCEM. Therefore, as compared to the baselines, the safety results of this analysis represent not only the effect of the UAS maneuvering vertically and coordinating, but also the effect of restricting its vertical rate (see Table I).

The baseline value for TCAS was 0.030 and the baseline value for ACAS Xa was 0.014.

C. Risk Ratio

The results of this analysis for encounters without coordination are depicted in Fig. 2. In this and subsequent figures, each of the three discrete vertical rate limits (VRL) imposed on the UAS is represented by a different color, while the changes to UAS vertical rate that occurred in conjunction with horizontal RAs are represented by the values on the X-axis. The baselines for both TCAS (orange) and ACAS Xa (black) are included within each graph, although individually each graph contains the results for encounters against one CAS or the other. Finally, the error bars represent 95% confidence intervals, calculated using a bootstrap approach [12].

Collision risk increased along with the maximum vertical rate of the UAS as well as the magnitude of its vertical rate changes. This trend was stronger for TCAS than for ACAS Xa, demonstrating that ACAS Xa is more robust to changes in intruder vertical rate than TCAS. Furthermore, for every combination of vertical rate parameters, ACAS Xa's collision risk was lower than that of TCAS.

As indicated by comparison to the TCAS vs. Unequipped baseline, no additional collision risk was induced against TCAS so long as the UAS's vertical rate changes were 500 fpm or less in magnitude. The same was true for ACAS Xa with one exception: when the UAS's vertical rate limit was 1500 fpm. However, note that collision risk with ACAS Xa was always below the TCAS baseline.

The results for encounters with coordination are depicted in Fig. 3. Responsive coordination, which constrains the vertical maneuvers of the UAS to be complementary to those of the manned aircraft, provided a substantial safety benefit. For ACAS Xa (Fig. 3b), collision risk with responsive coordination was always lower than the corresponding level without coordination. The same was true for TCAS (Fig. 3a) with one exception: when the UAS was limited to 500 fpm and changed its vertical rate by 500 fpm. However, given the large error bounds for this case, this difference may not be significant.

Furthermore, for both TCAS and ACAS Xa, collision risk with responsive coordination was below their respective baselines for all vertical rate parameters. The mitigating effect of coordination on collision risk was also stronger as the maximum vertical rate of the UAS increased.

These results demonstrate that collision risk increases when the vertical rate of the UAS changes suddenly towards the intended path of a manned intruder aircraft for this worst case analysis. Furthermore, the larger the change to vertical rate and the greater the vertical performance of the UAS, the larger the increase in collision risk. These results also suggest that if the UAS is limited to vertical rate changes of approximately 500 fpm or less following horizontal RAs, then safety is not degraded on TCAS or ACAS Xa against their respective baselines. Above 500 fpm, the use of responsive coordination is necessary to prevent safety degradation.

D. *RA Timing Differences*

One critical element of this analysis is the timing of the UAS's vertical rate changes. As discussed earlier, TCAS and ACAS Xa base their alerting decisions in large part on the projected vertical trajectories of intruders. Thus, it makes sense that the safety benefit of those alerting decisions would be affected by the relative timing of UAS vertical rate changes. If the UAS were to change its vertical rate long before TCAS or ACAS Xa issued an RA, then the RA selection would likely have taken this change to vertical rate into account. On the other hand, if the UAS were to change its vertical rate long after TCAS or ACAS Xa issued an RA, then it is likely that the encounter would already have been resolved by the time the change to vertical rate took place. However, if the UAS were to change its vertical rate at around the same time that TCAS or ACAS Xa issued an RA (the *collision avoidance timeframe*), then it is likely that the RA selection would not have taken the change to vertical rate into account, potentially leading to RA reversals and an increased collision risk. This is precisely what took place in the encounter depicted in Fig. 1.

In this study, the UAS changed its vertical rate in response to the initial horizontal RA issued in an encounter. Therefore, we can use the timing of the initial RAs issued by ACAS Xu as a proxy for the timing of the UAS's vertical rate changes.

Fig. 4a depicts a pair of probability distributions of the differences in initial alert timing between TCAS and ACAS Xu. One distribution represents only those encounters in which an NMAC was observed and the other represents all encounters. The particular distributions depicted in this figure correspond to those encounters in which the UAS had a vertical rate limit of 1500 fpm and changed its vertical rate by the same amount (statistics for other vertical rate limits and changes are outlined in Table II and Table III). Negative values indicate that ACAS Xu alerted after TCAS and positive values indicate that ACAS Xu alerted before TCAS.

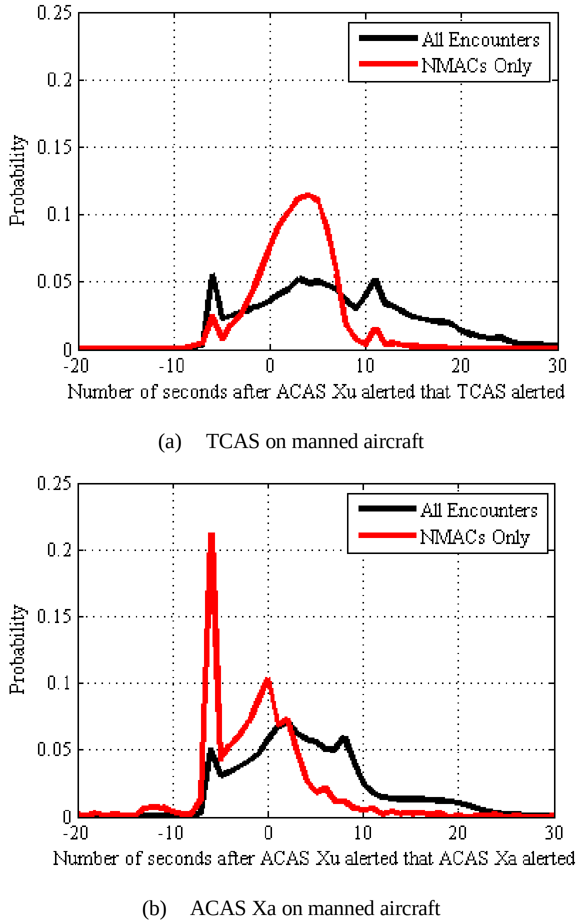


Figure 4. Probability distributions of relative RA timing

Among all encounters, TCAS alerted 7.0 seconds after ACAS Xu on average, while among the NMAC encounters, TCAS alerted 2.7 seconds after ACAS Xu on average. Furthermore, there is a noticeable difference in the spread of the distributions, with the NMAC-only encounters more tightly concentrated around their mean.

Fig. 4b contains the same probability distributions with ACAS Xa in place of TCAS.

The distributions for ACAS Xa are noticeably different from each other and from those of TCAS. The differences between TCAS and ACAS Xa are to be expected, as the two logics employ significantly different alerting criteria. As for ACAS Xu, among all encounters, ACAS Xa alerted 4.3 seconds after Xu on average, while among the NMAC encounters, ACAS Xa alerted 1.3 seconds before Xu on average.

There is a noticeable spike at –6 on the X-axis in every distribution of Fig. 4a and 4b. This spike represents encounters in which TCAS or ACAS Xa alerted 6 seconds before ACAS Xu. Not coincidentally, 6 seconds is one time step greater than the amount of time it took the manned aircraft to begin responding to the first RA it received in an encounter (see Table I). The spike exists because in many encounters, ACAS Xu alerted immediately after the manned aircraft began responding to its initial RA. As Fig. 4b shows, this behavior was a substantial factor in ACAS Xa's collision

TABLE II. ALERT TIMING STATISTICS FOR TCAS

UAS Vertical Rate Limit and Magnitude of Change (fpm)	Mean, Median, Standard Deviation (s)	
	All Encounters	**NMAC Encounters**
1500, 1500	7.0, 6, 8.4	2.7, 3, 4.2
1000, 1000	7.3, 7, 8.2	4.3, 4, 5.6
500, 500	6.5, 6, 7.9	8.7, 7, 10.3

TABLE III. ALERT TIMING STATISTICS FOR ACAS XA

UAS Vertical Rate Limit and Magnitude of Change (fpm)	Mean, Median, Standard Deviation (s)	
	All Encounters	**NMAC Encounters**
1500, 1500	4.3, 3, 6.9	–1.3, –1, 5.3
1000, 1000	4.4, 4, 6.9	0.7, 0, 8.0
500, 500	3.5, 3, 6.5	6.8, 6, 12.3

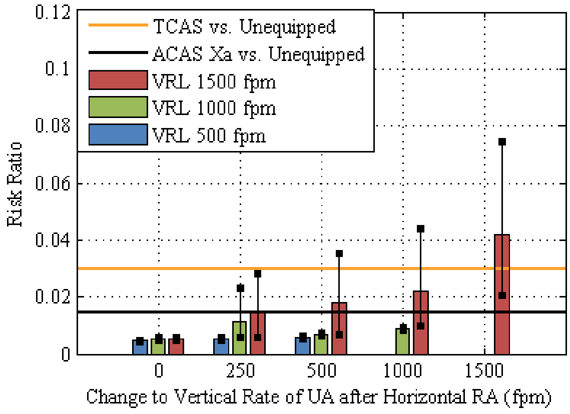
risk. The reason why has to do with an undesired RA reversal behavior that was present in the version of ACAS Xa simulated for this analysis. ACAS Xa remains under development, and this undesired behavior is not expected to be present in its future versions.

Table II and Table III contain statistics of the relative RA timing of ACAS Xu versus TCAS and ACAS Xa for the distributions depicted above as well as for two other sets of vertical rate parameters. As in the figures, positive values indicate that ACAS Xu alerted first.

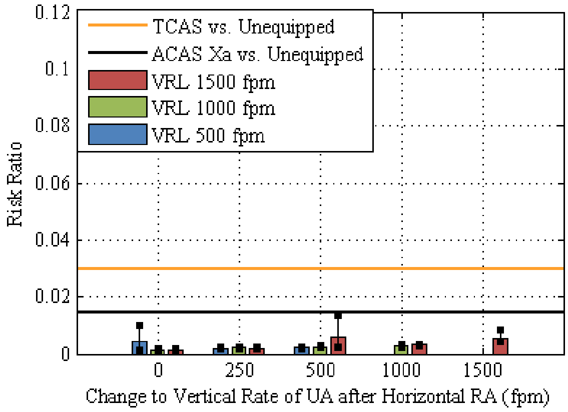
These results support the notion that the timing of the UAS's RAs and consequently its vertical rate changes affects the risk caused by those changes. Furthermore, the critical timing against one intruder CAS logic (such as TCAS) will not necessarily be the same as the critical timing against another intruder CAS logic (such as ACAS Xa). And finally, this critical timing depends in part on the magnitude of the UAS's vertical rate change.

E. UAS Horizontal Response

Fig. 5 depicts risk ratio for cases in which the UAS responds to ACAS Xu's horizontal guidance by turning. Note that responsive coordination was not active in this part of the analysis and that all other simulation parameters remained consistent with the previously detailed parts. When the UAS responded to horizontal RAs, collision risk decreased substantially against both TCAS and ACAS Xa. Mean collision risk decreased below the respective baselines of TCAS and ACAS Xa for every vertical rate parameter except one: encounters against TCAS when the vertical rate limit and change to vertical rate of the UAS were both ±1500 fpm.



(a) TCAS on manned aircraft



(b) ACAS Xa on manned aircraft

Figure 5. Risk ratio when the UAS turns in response to horizontal RAs, no coordination

IV. CONCLUSIONS

This analysis investigated the robustness of TCAS and ACAS Xa to sudden vertical maneuvers by an unmanned aircraft intruder employing ACAS Xu horizontal logic. Two safety baselines were established, one for TCAS and the other for ACAS Xa, as the risk ratio for each system in encounters against an intruder not receiving RA guidance. Using these baselines, the results suggest the following for the worst-case scenario in which, following its horizontal RAs, the UAS maneuvered vertically towards the manned intruder and did not turn:

- Collision risk is elevated above the baselines when the UAS changes its vertical rate by more than 500 fpm within the manned aircraft's collision avoidance timeframe if responsive coordination is not employed.
- Responsive coordination lowers collision risk below the baselines for all UAS changes to vertical rate and vertical rate limits.

An analysis of the relative timing of the RAs issued by the unmanned and manned aircraft revealed a critical timeframe when vertical maneuvers by the UAS were most dangerous. This timeframe was different for TCAS and ACAS Xa and also varied with the vertical performance of the UAS.

Collision risk decreased substantially when the UAS turned in response to ACAS Xu's horizontal RAs, with all results below the baseline of ACAS Xa and all except one below the baseline of TCAS: when the UAS was most capable (vertical rate limit ±1500) and changed its vertical rate by the largest amount (1500 fpm).

By considering separate baselines for TCAS and ACAS Xa, these results show the robustness of each system individually against the vertical maneuvers of the UAS. However, when compared against one another, ACAS Xa consistently showed superior safety performance to that of TCAS. Also, although TCAS logic is not expected to change, ACAS Xa is still under development, and so future iterations could produce further improvements in safety performance.

There are many opportunities for future work in this area. For example, while this analysis shed light on the importance of relative RA timing, relative RA timing itself was not an independent variable – it depended on the simulated CAS logics. Future studies should recast relative RA timing as an independent variable, which will allow for a direct comparison of collision risk to the timing of vertical maneuvers on the UAS. Other potential future work could replicate this study with alternate CAS and self-separation logics, surveillance sources, and encounter sets.

Finally, it is important to keep in mind that the results of this analysis are specific to the behavior of a single system providing horizontal guidance and employing noiseless surveillance against a pair of specific vertical collision avoidance systems, as well as to the baselines chosen for this analysis. Any recommendations based on these results must include these caveats.

ACKNOWLEDGMENTS

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