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Safety Analysis of Upgrading to TCAS Version 7.1 Using the 2008 U.S. Correlated Encounter Model

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16. Abstract

As a result of monitoring and modeling efforts by Eurocontrol and the FAA, two change proposals have been created to change the TCAS II V7.0 logic. The first, CP-112E, addresses the safety issues referred to as SA01. SA01 events have to do with the reversal logic contained in the TCAS algorithm, e.g. when TCAS reverses the sense of an RA from climb to descend. Typically, reversals occur to resolve deteriorating conditions during an encounter. V7.0 contained reversal logic based on certain assumptions and engineering judgment, but operational experience obtained since deployment has compelled a re-evaluation in areas of that logic, specifically having to do with late reversals. The second change proposal, CP-115, rectifies observed confusion surrounding the aural annunciation AVSA during an RA by replacing it with the annunciation LOLO, and changing the TCAS V7.0 display and logic to appropriately support the change. Collectively, the changes to the TCAS logic in both CP-112E and CP-115 are referred to as TCAS II V7.1.

Included in this document is a safety study that considers V7.1 as a whole, and also the first safety study that uses the U.S. correlated encounter model developed by Lincoln Laboratory for testing TCAS. Also included is a discussion of simulation capabilities developed at Lincoln Laboratory for evaluating CP-115 and for future analysis of TCAS in high density areas. Our study indicates that more risk lies in remaining with the current version of TCAS over upgrading to V7.1, and that no negative impact on safety in high density airspace occurs as a result of CP-115.

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EXECUTIVE SUMMARY

As a result of monitoring and modeling efforts by Eurocontrol and the Federal Aviation Administration (FAA), two change proposals have been created to change the Traffic Alert and Collision Avoidance System (TCAS) II V7.0 logic. The first, CP-112E, addresses the safety issues referred to as SA01. SA01 events have to do with the reversal logic contained in the TCAS algorithm, e.g. when TCAS reverses the sense of an Resolution Advisory (RA) from climb to descend. Typically, reversals occur to resolve deteriorating conditions during an encounter. V7.0 contained reversal logic based on certain assumptions and engineering judgement, but operational experience obtained since deployment has compelled a re-evaluation in areas of that logic, specifically having to do with late reversals. The second change proposal, CP-115, rectifies observed confusion surrounding the aural annunciation "Adjust Vertical Speed, Adjust" (AVSA) during an RA by replacing it with the annunciation "Level Off, Level Off" (LOLO), and changing the TCAS V7.0 display and logic to appropriately support the change. Collectively, the changes to the TCAS logic in both CP-112E and CP-115 are referred to as TCAS II V7.1.

Version 7.1 of TCAS has the potential to significantly improve the operation of TCAS in certain deteriorating encounter conditions such as SA01 type encounters. In addition, it includes changes to the logic to rectify potential confusion surrounding AVSA resolution advisories, thereby reducing the incidence of pilot responses in the opposite direction of what was intended by the RA. Previous safety studies by Eurocontrol and the RTCA have confirmed the benefits to CP-112E and CP-115 in separate studies using encounter models previously developed for Europe and the United States.

Included in this document is a safety study that considers V7.1 as a whole, and also the first safety study that uses the U.S. correlated encounter model developed by Lincoln Laboratory for testing TCAS. Also included is a discussion of simulation capabilities developed at Lincoln Laboratory for validating the Eurocontrol CP-115 study and for future analysis of TCAS in high density areas. Finally, included as an appendix is confirmation that a minor change to the green-arc-on-weakening logic will not affect the performance of TCAS in one on one encounters.

We created 500,000 sample encounters from the U.S. correlated encounter model in order to test the safety of V7.1. We then used our simulation environment, CASSATT, to run the encounters in simulation under various equipage and pilot response combinations, and computed metrics such as risk ratios and Near Mid-Aid Collision (NMAC) rates. In aggregate over every equipage and pilot response combination simulated, V7.1 lowered the risk of NMAC over V7.0, in some cases substantially.

- The risk ratio for V7.1 when both aircraft respond to their RAs is 1.59%, compared to 1.61% with V7.0.

- The risk ratio for V7.1 when one aircraft does not respond to their RAs is 9.61%, compared to 9.85% with V7.0.
- The risk ratio for V7.1 vs. unequipped-intruder encounters is 12.29%, compared to 12.45% with V7.0.
- When V7.1 changes the vertical miss distance (VMD) compared to V7.0, VMD increases 91% of the time.

All supporting metrics support the same conclusion, that more risk lies in remaining with the status-quo over upgrading to V7.1.

The new U.S. correlated encounter model is very different than the most recent airspace encounter model created by Eurocontrol, leading to lower risk ratios, but higher overall NMAC rates. One of the major differences between the new U.S. correlated model and the European model is the encounter rate. The encounter rate in the United States is 0.0163 encounters/fl.hr., or one encounter every 61.3 flight hours. By comparison, the encounter rate observed in European studies was 0.0023 encounters/fl.hr., or one encounter every 431.5 flight hours [1]. The encounter rate in the United States is 7 times higher than what was observed in European airspace during creation of the European model. The higher encounter rate in the United States is likely due to a higher density of air traffic in general, and higher levels of VFR traffic in particular, especially in Class E airspace where most encounters occur. At the same time, the U.S. correlated encounter model produces a probability of NMAC without TCAS of 0.0030 per encounter, slightly higher than the corresponding probability of NMAC from the European model (0.0028). The modeled U.S. NMAC rate is therefore also about 7 times higher than in Europe. The higher baseline NMAC rate affects every statistic in the study, including both risk ratios and rate metrics.

Another major difference between the two models is the distribution of vertical maneuvers for aircraft during encounters. In the United States, between 60% and 75% of aircraft involved in encounters are in level flight (depending on altitude layer), whereas in Europe, only between 35% and 55% of aircraft involved in encounters are flying level. Vertical maneuvering, especially for the threat aircraft, is known to degrade TCAS performance due to estimation error of the altitude tracker. Thus, although the encounter rate in the United States is higher, the mix of encounters in the U.S. Correlated Encounter Model is less challenging to TCAS than what was observed in Europe, which contributes to lower risk ratios.

There are also major differences between the new U.S. correlated encounter model and the previous U.S. encounter model developed by MITRE in the early 1990s. There have been significant changes in the U.S. airspace since the last U.S. encounter model was created, including the rise of regional jet fleets, the use of reduced vertical separation at higher altitudes, and increased traffic densities. Differences in the models have led to different patterns in the risk ratio results. Still, risk ratios observed using the new U.S. encounter model are comparatively closer in value to the older U.S. encounter model than they are to the risk ratios observed using the European model.

The study to determine the safety of CP-115 in a busy terminal airspace was based on 518 AVSA encounters observed from the MIT Lincoln Laboratory MODSEF surveillance radar between March 2006 and June 2008. In our data set, 15% of encounters involve an AVSA but only 25% of AVSA encounters would be affected by CP-115. These numbers imply that approximately 3.7% of RAs in the Boston airspace would be affected by CP-115. Exposure to cases where a LOLO RA could induce an RA with a third party aircraft, defined as within 10 NM and 10,000 ft, is low: two-thirds of the observed encounters affected by CP-115 have a third party aircraft in the vicinity at the time of the RA.

Using CASSATT, we were able to replicate about 25% of the observed downlink sequences and third party aircraft. In simulation, we equipped the TCAS aircraft in those encounters with both V7.0 and V7.1, and observed the effect on safety. In summary we found:

- CP-115 increases separation with the intruder aircraft.
- CP-115 also generally increases separation with third party aircraft, although there is no algorithmic reason in the logic that should imply this result.
- CP-115 did not induce any additional RAs with third party aircraft in our analysis.

These results validate the findings previously reported by Eurocontrol [2].

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1. INTRODUCTION

As a result of monitoring and modeling efforts by Eurocontrol and the FAA, two change proposals have been created to change the Traffic Alert and Collision Avoidance System (TCAS) II V7.0 logic. The first, CP-112E, addresses the safety issues referred to as SA01. SA01 events have to do with the Resolution Advisory (RA) reversal logic contained in the TCAS algorithm, e.g. when TCAS reverses the sense of an RA from climb to descend. Typically, reversals occur to resolve deteriorating conditions during an encounter. V7.0 contained reversal logic based on certain assumptions and engineering judgement, but operational experience obtained since deployment has compelled a re-evaluation in areas of that logic, specifically having to do with late reversals.

The SA01 issue was originally discovered by European modeling analyses in early 2000, and was subsequently detected during monitoring efforts from 2001 to 2005. It is believed that this issue was a factor in two major recent events: a near mid-air collision (NMAC) in Japanese airspace between a B-747 and a DC-10-40 on 31 January 2001 (resulting in injuries), and the mid-air collision between a B-757 and a Tu-154 over Überlingen, Germany on 1 July 2002. In both these accidents, TCAS failed to reverse the sense of its initial RA even though a reversal might have prompted action to avoid the accident [3]. Since 2000, other SA01 events have been detected through monitoring efforts in European airspace, Japanese airspace and U.S. airspace.

The second change proposal, CP-115, rectifies observed confusion surrounding the aural annunciation "Adjust Vertical Speed, Adjust" (AVSA) during an RA by replacing it with the annunciation "Level Off, Level Off" (LOLO), and changing the TCAS V7.0 display and logic to appropriately support the change. AVSA RAs, introduced with TCAS V7.0, were included in the logic to allow pilots to continue their climb or descent, but to adjust their vertical speed to avoid a potentially dangerous situation with a nearby aircraft. They broadly fall under two categories: weakening RAs and vertical rate magnitude reductions. Weakening RAs resulting in AVSAs include "Do Not Climb" and "Do Not Descend" RAs; these RAs are unaffected by CP-115. Vertical rate magnitude reduction RAs include instructions to limit a climb or descend to a certain vertical speed; for instance, to ± 500, 1000 or 2000 ft/min. The recommended vertical speed to achieve is indicated by a green bar on the pilot's vertical speed indicator, as shown in Figure 1. CP-115 changes the aural annunciation for all AVSA vertical rate reductions to "Level Off, Level Off", and changes the accompanying TCAS display to indicate that a level off maneuver will satisfy the RA.

The change from AVSA RAs to LOLO RAs was originally proposed by Eurocontrol as a result of monitoring efforts between 2001 and 2005 [4, 5]. Data from that collection effort indicated an unexpectedly high number of observed AVSA RAs resulted in vertical rate changes by the pilot in the opposite direction to the vertical speed recommended by TCAS. Rather than decreasing their climb rate, for example, pilots instead began to increase their climb rate. In effect, the opposite response was mitigating the intended result of allowing AVSA RAs in the first place, namely, to allow better compliance with issued Air Traffic Control (ATC) altitude clearances.

Collectively, the changes to the TCAS logic in both CP-112E and CP-115 are referred to as TCAS II V7.1. Before allowing operators to update their TCAS systems, however, the safety of the new system needs to be assessed. One component of a safety analysis is to test the system in

Figure 1. Examples of TCAS vertical speed displays for some common RAs. Far left: "Descend, Descend." Center left: "Adjust Vertical Speed, Adjust" (0 fpm). Center right: "Adjust Vertical Speed, Adjust" (2000 fpm). Far right: "Climb, Climb." The aircraft's current vertical speed is indicated by the bright red needle on the instrument. [6]

simulation. MIT Lincoln Laboratory has recently completed a correlated encounter model of the National Airspace System (NAS) [7]. The correlated encounter model produces realistic trajectories for aircraft involved in encounters where at least one of the aircraft is under ATC control. Using this model, a Monte Carlo analysis may be performed whereby the system is exposed to millions of realistic situations, and we can assess the efficacy of the system in reducing the probability of a NMAC. This type of analysis is appropriate for measuring the impact of CP-112E, because many times more SA01 events can be simulated than have been observed. At the same time, the rate of SA01 events per encounter will remain realistic. It is also appropriate for CP-115, because that change may also impact the probability of NMAC in simulation.

We also investigated the potential impact of CP-115 in a real, high density airspace. As stated before, it was originally believed that AVSA RAs would better comply with ATC clearances, and that due to the structure of the airspace, especially around busy terminal areas, pilots leveling off due to a LOLO RA, while avoiding the threat aircraft, may induce a conflict with a third party aircraft. The correlated encounter model, however, only includes pairwise encounters between aircraft, and does not model additional aircraft in the vicinity of the encounter. Therefore, we recreated actual observed encounters in the Boston, MA airspace, including third party aircraft, to evaluate the impact of CP-115.

There have been three other major studies performed to evaluate the safety of V7.1. The first, published by the RTCA, evaluated the safety of CP-112E [3]. This study utilized the most recent encounter model developed by Eurocontrol for the European airspace, the most recent ICAO encounter model which included some US data [8], and the original US encounter model developed by MITRE in the 1980s and 1990s. The second study, published by Eurocontrol, evaluated the impact of CP-115 in Boston airspace [2]. The third study, to be published by MIT Lincoln Laboratory and the FAA Technical Center, used the FAA's Fast Time Encounter Generator to evaluate the safety of V7.1. All of these studies concluded the benefits of upgrading the TCAS logic outweighed the risks.

Section 2 describes the impact of V7.1 on safety using the correlated encounter model. Section 3 compares and contrasts the results presented in this report against several prior analyses. Section 4 describes the predicted operational impact of CP-115 in a busy terminal airspace (e.g. Boston). In Appendix C we describe activities to verify that a minor change to the display logic had no effect on the operation of resolution advisory logic in one on one encounters.

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2. ENCOUNTER MODEL ANALYSIS

2.1 PURPOSE

One purpose of this study was to use the newly constructed U.S. correlated encounter model to evaluate V7.1. An encounter model provides the ability to produce millions of realistic dangerous encounter situations within an approximately one-minute window surrounding the Time of Closest Approach (TCA). Encounter models have been employed to certify the safety of TCAS since the early 1980s [9], but the last encounter model incorporating surveillance data from the United States was in the early 1990s [8]. The most recent encounter models were developed by Eurocontrol, and have been most recently employed to investigate the safety of CP-112E [3].

The U.S. correlated model developed by Lincoln Laboratory incorporates 9 months of nationwide surveillance data between December 1, 2007 and August 31, 2008, resulting in over 24 million observed flight hours and 393,077 observed encounters between aircraft [7]. The encounters were captured using a filter designed to identify one on one encounters in the NAS that TCAS would be expected to safely resolve. The main feature of the new model, beyond the large quantity of US data used to construct it, is the fact that simulated aircraft tracks sampled from the model were allowed to change their vertical rate and turn rate at any point in time over the course of the encounter. By comparison, all prior models only permitted a single maneuver over the course of the encounter.

This section describes the results from evaluating the safety impact of V7.1 using the U.S. correlated encounter model. Section 2.2 describes the methods used to sample from the model and simulate encounters. Section 2.3 describes the results from a safety evaluation of V7.1.

2.2 METHODS

2.2.1 Encounter Generation

We utilized importance sampling techniques in order to increase the precision in our results. Importance sampling is a well understood variance reduction technique used very frequently in Monte Carlo studies such as the the one in this report. Further details about how we used importance sampling for this study can be found in Appendix D. We used 500,000 weighted sample encounters from the U.S. correlated model to conduct our analysis.

2.2.2 Test Plan and Simulation

Each of the 500,000 sampled encounters is simulated under various TCAS and transponder equipage and pilot response model combinations. The equipage options are:

- **Mode C:** The aircraft is equipped with a Mode C altitude transponder which reports altitude in 100 ft quanta.
- **Mode S:** The aircraft is equipped with a Mode S altitude transponder which reports altitude

in 25 ft quanta.

- **V7.0:** The aircraft is equipped with a TCAS unit with the Version 7.0 software, and a Mode S transponder with 25 ft altitude quantization.

- **V7.1:** The aircraft is equipped with a TCAS unit with the Version 7.1 software, and a Mode S transponder with 25 ft altitude quantization.

The relevant altitude error models depend upon the transponder equipage, and this altitude error distribution in turn affects the probability of Near Mid-Air Collision, P(NMAC) [3,8]. Pilot response to an RA follows either the ICAO standard (5 s delay followed by 0.25 g vertical acceleration to the target rate) or a no-response case in which the RA is ignored [8]. In addition, the TCAS coordinated maneuver logic functions differently depending on the relative rank of own aircraft's Mode S address compared to the threat aircraft's Mode S address, so this is varied for each condition as well when TCAS is equipped on board both aircraft.

Our simulation environment is described in Appendix A.

2.3 RESULTS

This section describes the results from our simulation analysis. We assessed the safety of V7.1 and V7.0 against intruders equipped with V7.1, V7.0, and unequipped with TCAS (but equipped with Mode C transponders). We also assessed the safety of each version against intruders equipped with TCAS but not responding to RAs. In general, most tables and figures presented in this section correspond to tables and figures in RTCA DO-298, which evaluated the safety impact of CP-112E [3]. Differences in results in this section versus what was documented in DO-298 were due either to the model or the fact that V7.1 includes both CP-112E and CP-115; some of those differences are discussed in Section 3.

2.3.1 Risk Ratio

A common metric that incorporates $P(\text{nmac} \mid \text{enc})$ is the risk ratio, which compares the $P(\text{nmac} \mid \text{enc})$ resulting from equipping one or more aircraft during the encounter with TCAS versus the nominal encounter condition where neither plane is equipped with TCAS [3]. A typical safety study consists of one or more Monte Carlo simulations that permits an unbiased estimate of $P(\text{nmac} \mid \text{enc}, \text{equip})$. The variable "equip" signifies the equipage on the two aircraft involved in the simulation. For instance, consider three equipage combinations for the two aircraft involved in the encounter: Unequipped/Unequipped (UU), TCAS/Unequipped (TU), and TCAS/TCAS (TT). The equipage option "unequipped" signifies that the aircraft has an altitude reporting transponder but no TCAS, and the option "TCAS" signifies the aircraft is equipped with TCAS V7.0. Using samples from our encounter model and our simulation environment, we can calculate the risk ratios including

$$RR_1 = \frac{P(\text{nmac} \mid \text{enc}\,, \text{TU})}{P(\text{nmac} \mid \text{enc}\,, \text{UU})} \quad \text{and} \quad RR_2 = \frac{P(\text{nmac} \mid \text{enc}\,, \text{TT})}{P(\text{nmac} \mid \text{enc}\,, \text{UU})}\,.$$

The baseline (non-TCAS) value for $P(\text{nmac} \mid \text{enc})$ in the U.S. correlated encounter model was found to be approximately 0.003.

If we assume the intruder is unequipped but is carrying an altitude-reporting transponder, equipping the own-aircraft with TCAS will reduce NMAC risk by $(1 - RR_1) \cdot 100$ percent. If two unequipped aircraft in an encounter had been equipped with TCAS, the NMAC risk would have been reduced by $(1 - RR_2) \cdot 100$ percent. It is also possible, as we do in this report, to vary other encounter parameters, including pilot response models and versions of TCAS, and compare effects on risk ratio.

Table 1 shows the risk ratios observed when both aircraft are equipped with TCAS. One row is used for cases in which both aircraft follow the standard RA response, and a second row is used for cases in which one aircraft follows the standard response but the intruder ignores its RA.

Under standard response conditions for both aircraft, we found a decrease in risk ratio from V7.0–V7.0 encounters (1.61%) to V7.1–V7.1 encounters (1.59%). The result seen in this study has been attributed primarily to the addition of CP-115 in V7.1. These results indicate that if all aircraft were equipped with V7.1, and all pilots responded to their RAs as indicated, the number of NMACs in our model of the NAS would be reduced by 98.41%.

For the standard/no-response cases, risk ratio is also lower in V7.1–V7.1 encounters (9.61%) than in V7.0–V7.0 encounters (9.85%). This reduction in risk ratio is likely due to improved handling from CP-112E in late or no-response (SA01a) conditions, as well as the effect of including CP-115.

Mixed-version scenarios in which one aircraft is equipped with V7.0 and the other is equipped with V7.1 result in a risk ratio about halfway between the risk ratios when both are equipped with V7.0 or both are equipped with V7.1. V7.1 increases safety even in mixed version scenarios, under both standard (1.60%) and no-response (9.69%) conditions. Thus, this study indicates that safety will still be improved even during a period of time where V7.1 must interact with existing V7.0 TCAS units.

TABLE 1

Risk ratios for TCAS-TCAS encounters. Probability of NMAC without TCAS, including altitude error, is 0.0031.

	Equipage		
Pilot Response Model	V7.0 – V7.0	V7.0 – V7.1	V7.1 – V7.1
Standard–Standard	1.61%	1.60%	1.59%
Standard–No Response	9.85%	9.69%	9.61%

Table 2 shows the risk ratios for V7.0 and V7.1 versus unequipped intruders. Risk ratio is slightly lower for V7.1–unequipped encounters (12.29%) than for V7.0–unequipped encounters

(12.46%). The improvement in risk ratio can be attributed to the improvement in handling SA01b cases, as well as the effect of including CP-115.

TABLE 2

Risk ratios for TCAS-unequipped encounters (standard pilot response model). Probability of NMAC without TCAS, including altitude error, is 0.0032.

Version 7.0	12.46%
Version 7.1	12.29%

2.3.2 Supporting Metrics

Table 3 shows unresolved and induced probabilities and NMAC rates per flight hour for encounters between aircraft equipped with TCAS for various response conditions. We observed a rate of 0.0163 encounters per flight-hour. Unresolved NMACs are defined as NMACs that occur both with and without TCAS. Induced NMACs are defined as NMACs that occur only with TCAS. Therefore,

$$RR_{unresolved} = \frac{P(\text{nmac} \mid \text{enc}\,,\text{unresolved})}{P(\text{nmac} \mid \text{enc}\,,\text{UU})} \quad \text{and} \quad RR_{induced} = \frac{P(\text{nmac} \mid \text{enc}\,,\text{induced})}{P(\text{nmac} \mid \text{enc}\,,\text{UU})}\,.$$

Unresolved risk ratio is equivalent to the percentage of NMACs that were unresolved by TCAS. Likewise, induced risk ratio is equivalent to the percentage of NMACs that were induced by TCAS. Unresolved and induced risk ratio sum to the overall risk ratio.

TABLE 3

Unresolved and induced probabilities (rates) for TCAS-TCAS encounters. Rates are per flight hour, based on 0.0163 encounters/fl.hr.

Pilot Response Model	Equipage	Unresolved	Induced
Standard – Standard	V7.0 – V7.0	1.30% ($6.57 \cdot 10^{-7}$)	0.31% ($1.59 \cdot 10^{-7}$)
	V7.1 – V7.1	1.28% ($6.48 \cdot 10^{-7}$)	0.31% ($1.57 \cdot 10^{-7}$)
Standard – No Response	V7.0 – V7.0	5.36% ($27.2 \cdot 10^{-7}$)	4.49% ($22.8 \cdot 10^{-7}$)
	V7.1 – V7.1	5.34% ($27.0 \cdot 10^{-7}$)	4.27% ($21.6 \cdot 10^{-7}$)

As shown in Table 3, V7.1 decreases both the unresolved and induced risk between aircraft equipped with TCAS for both standard and non-responding intruders. The greatest difference between the two versions is the likelihood of an induced NMAC when the intruder does not respond to its RA. In that event, when both aircraft are equipped with V7.1, the induced risk ratio decreases from 4.49% to 4.27%. An induced collision due to a non-response or late response is typical of SA01a events, and so reflects the effect of CP-112E.

The table also emphasizes the danger of non-response; by not responding to TCAS, the risk of an unresolved NMAC increases by over 4 fold, and the risk of an induced NMAC increases by about 14 fold for both versions of TCAS. It is important to reiterate, however, that standard responses only very rarely induce an NMAC.

Two other metrics were defined in DO-298 to aid in representing the decision risk involved in whether to upgrade V7.0 to V7.1. The status-quo risk rate represents the rate with which an NMAC will occur that would have been prevented had TCAS been upgraded with V7.1 on all aircraft in the airspace. The upgrade risk rate represents the rate with which an NMAC will occur under V7.1 that would have been prevented had TCAS not been changed from V7.0. Table 4 shows status-quo and upgrade risk rates per flight hour for encounters for various equipage scenarios (all referenced to an order of magnitude of 10^{-9}).

TABLE 4

Status-quo and upgrade risk rates. Rates are per flight hour.

Situation	Status Quo	Upgrade
TCAS–TCAS (Standard–Standard)	$11.8 \cdot 10^{-9}$	$0.67 \cdot 10^{-9}$
TCAS–TCAS (Standard–No Response)	$187 \cdot 10^{-9}$	$6.3 \cdot 10^{-9}$
TCAS–Unequipped (Standard–No Response)	$105 \cdot 10^{-9}$	$1.6 \cdot 10^{-9}$

Table 4 shows that the change is highly effective at reducing the risk of NMAC. The risk of remaining with the status quo (V7.0) in encounters against non-responding intruders ($1.87 \cdot 10^{-7}$) is about 3.7 times higher than the risk of upgrading to V7.1 ($0.63 \cdot 10^{-8}$) and the risk of remaining with the status quo in encounters against unequipped intruders ($1.05 \cdot 10^{-7}$) is about 8 times higher than the risk of upgrading ($0.16 \cdot 10^{-8}$). The status-quo risk rate is 10 times higher for encounters with non-responding intruders than for encounters with responding intruders. This is expected, since CP112-E was designed to improve SA01 encounters (late or no response on the part of the intruder), and was designed not to affect standard response encounters. We also found a reduction in risk rate in upgrading from V7.0 to V7.1 under standard response conditions. This reduction is reflected in the risk ratios from Table 1, and is primarily a function of the inclusion of CP-115 in the logic.

Figure 2 graphically depicts decision risk curves for various response rates in the airspace. These curves plot the risk of either upgrading to V7.1 or staying with V7.0 versus possible RA response rates in the airspace. The decision risk curve is particularly useful because, overall, pilots respond to their RAs less than 100% of the time. Regardless, under all response rate conditions possible in the NAS, we found that more overall risk lies in staying with V7.0.

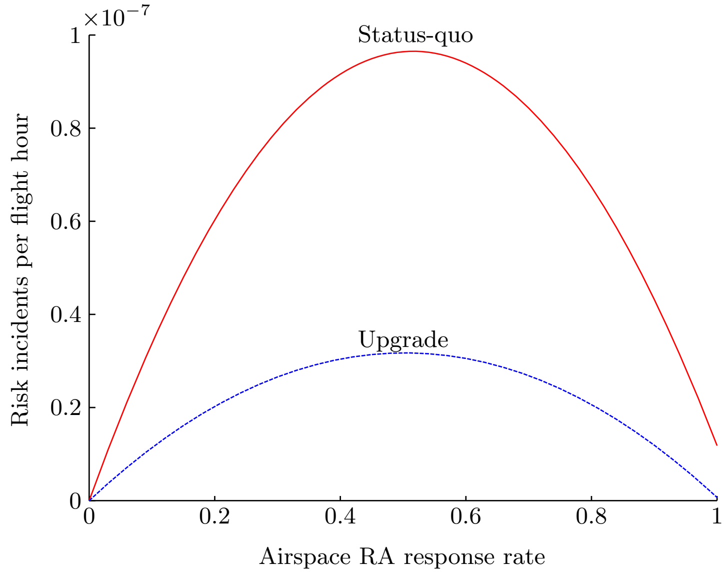

Figure 2. Decision risk versus airspace RA response rate. Results presented for TCAS/TCAS encounters and 25 ft encoding.

Most encounters result in the same miss distance with V7.0 and V7.1. Figure 3 and Figure 4 depict distributions of changes in Vertical Miss Distance (VMD) between V7.0 and V7.1. Each data point represents a single encounter scenario, showing the separation under V7.1 (y-axis) versus under V7.0 (x-axis). When the threat aircraft is equipped with TCAS but not responding (Figure 3), V7.1 increases VMD 91% of the time when there is a change in VMD.

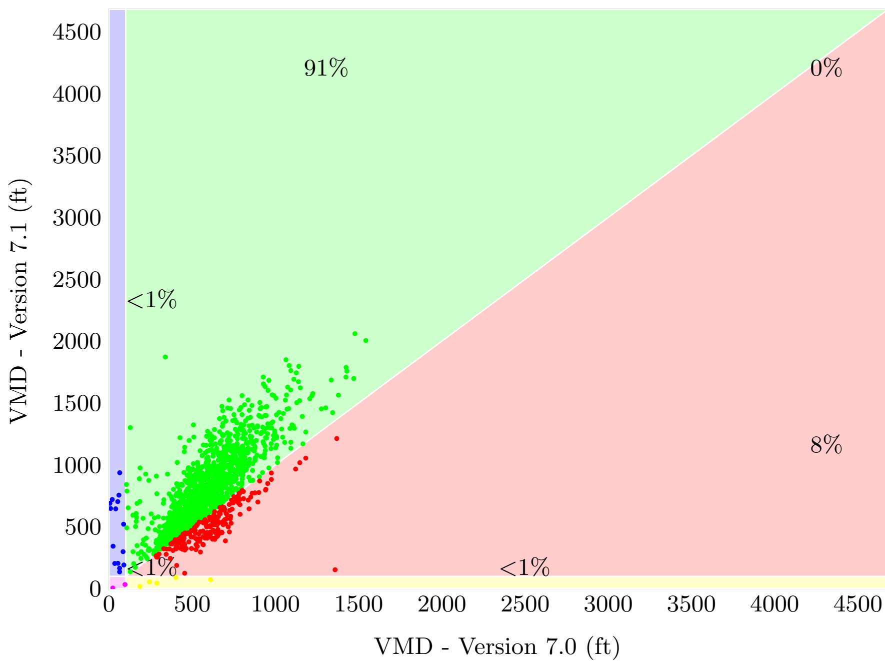

Figure 3. Vertical miss distance for TCAS–TCAS (Standard-No response) encounters. Only 2,500 encounter data points where VMD for V7.1 is different from V7.0 are shown, but percentages represent all encounters where VMD was changed. Encounters where VMD was unaffected by V7.1 were not included. VMD is defined at the point of minimum horizontal separation between the two aircraft.

Similarly, when the threat aircraft is unequipped with TCAS, V7.1 increases VMD over V7.0 92% of the time (Figure 4).

V7.1 is highly effective at increasing vertical separation between aircraft, above and beyond that of V7.0, relatively infrequently causes vertical separation to decrease, and only very rarely causes separation to decrease to below 100 ft.

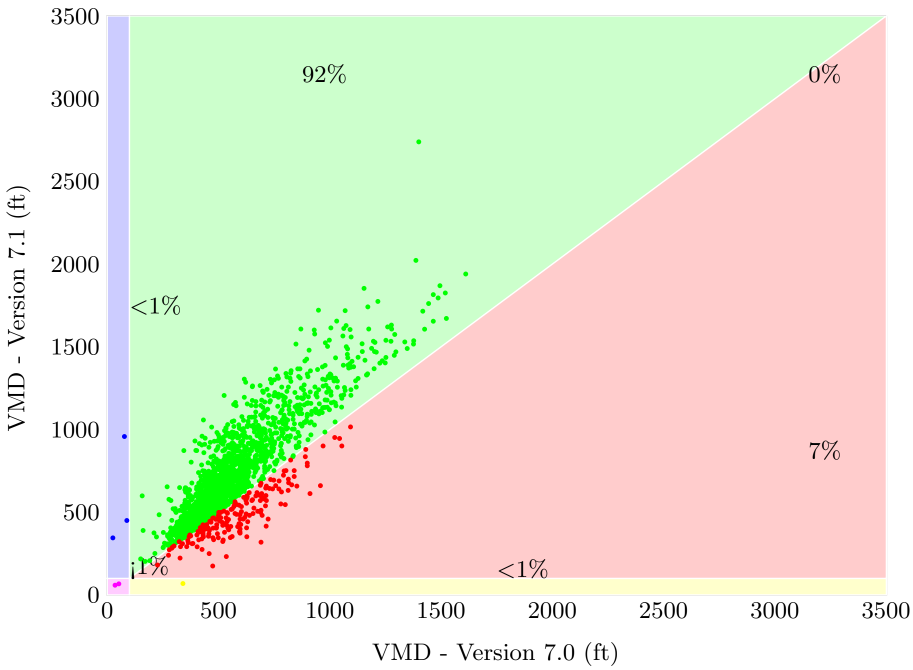

Figure 4. Vertical miss distance for TCAS (Standard)–Unequipped intruder encounters. Only 2,500 encounter data points where VMD for V7.1 is different from V7.0 are shown, but percentages represent all encounters where VMD was changed. Encounters where VMD was unaffected by V7.1 were not included. VMD is defined at the point of minimum horizontal separation between the two aircraft.

2.4 SUMMARY

In summary, we found that V7.1 improves the overall safety of TCAS regardless of intruder equipage or pilot response.

The risk ratio for V7.1 when both aircraft respond to their RAs is 1.59%, lower than the comparable risk ratio with V7.0 (1.61%). The risk ratio for V7.1 when one aircraft does not respond to their RAs is 9.61%, which is lower than the comparable risk ratio with V7.0 (9.85%). The risk ratio for V7.1 vs. unequipped-intruder encounters is 12.29%, which is lower than the comparable risk ratio with V7.0 (12.45%). All supporting metrics provide the same conclusion: that more risk lies in remaining with the status-quo over upgrading to V7.1.

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3. COMPARISON WITH PRIOR STUDIES AND MODELS

The U.S. correlated encounter model is the most recent in a series of airspace models developed since the 1980s. This section compares the results from this safety study to results achieved using prior encounter models, specifically found in DO-298, an RTCA document containing the results from a safety study specifically of CP-112E [3]. In DO-298, both Eurocontrol and Lincoln Laboratory ran Monte Carlo analyses of CP-112E using their own implementations of the European encounter model.

3.1 COMPARISON TO EUROPEAN MODEL

There are significant differences between European airspace of the early part of this decade and current U.S. airspace. Major differences between European airspace and U.S. airspace include different ATC procedures, traffic densities and encounter rates, and a greater amount of VFR traffic in the United States as compared to Europe.

In addition, our encounter model was built using data from a relatively large amount of en-route airspace. The European model was built using data from radars in southern England and France, which includes a greater ratio of terminal to en-route traffic than was observed in our data set. Terminal traffic and en-route traffic greatly differ in terms of aircraft maneuvering and airspace structure.

All of these factors, combined with the differences in the way we processed the surveillance data and the model structure itself, have produced a different model than the European model used to test TCAS in DO-298. A brief explanation of two major differences between the models will help explain some of the results. However, there are other differences between the two models beyond the two differences discussed in this report.

3.1.1 Risk Ratios

DO-298 contained risk ratios calculated from using the European model in Monte Carlo simulation. Some of the previous Lincoln Laboratory results using the European encounter model are reproduced here in Table 5 and Table 6. These tables correspond to Table 6-3 and Table 6-4 in DO-298 respectively.

The risk ratios calculated using the U.S. correlated model (Table 1 and Table 2) are lower than the risk ratios calculated previously using the European model, and in the case of non-responding intruders are much lower. In addition, in DO-298, there was a slight increase in risk ratio (compared to V7.0) when both aircraft responded to their RAs and were equipped with CP-112E when using the European model. The decrease in risk ratio found under the same conditions in our current study has been attributed to the inclusion of CP-115 in V7.1, which was not included in the prior analyses.

An explanation of the generally higher risk ratios observed using the European model follows.

TABLE 5

Risk ratios for TCAS-TCAS encounters using the European encounter model (25 ft quantization). [3]

	Equipage		
Pilot Response Model	V7.0 – V7.0	V7.0 – V7.1	V7.1 – V7.1
Standard–Standard	2.0%	2.0%	2.0%
Standard–No Response	23.1%	21.7%	20.2%

TABLE 6

Risk ratios for TCAS-unequipped encounters (standard pilot response model) using the European encounter model (25 ft quantization). [3]

Version 7.0	23.1%
Version 7.1	22.1%

3.1.2 Aircraft Maneuvering

A major difference between the two models is that the aircraft observed in U.S. airspace who are involved in encounters tend to maneuver differently than the aircraft involved in encounters that were used to construct the European encounter model. The Europeans considered aircraft vertical profiles during the encounter period to fall into one of eight maneuver classifications, depending on their observed vertical rates over the course of the encounter. Maneuver classification involved identifying, using procedures outlined as part of the ACAS Analysis Programme (ACASA) model documentation, vertical acceleration periods for tracks and then classifying the vertical rates before and after the acceleration period as Level (L), Climb (C) or Descend (D) [1]. Accordingly, the maneuver code for the figures is as follows:

- DD: Descent
- LD: Start of Descent
- CD: Overshoot
- DL: End of Descent
- LL: Level
- CL: End of Climb
- DC: Undershoot
- LC: Start of Climb
- CC: Climb

Unlike the European model, the U.S. correlated encounter model does not explicitly calculate the statistical distribution of these various maneuvers and include them as a variable in the model.

Instead, maneuver categories are implicitly included in our model as a result of the dynamic motion of the aircraft captured in our dynamic model. However, because the maneuver variable has a significant impact on risk ratio for encounters sampled from the European model, maneuver classifications for U.S. encounters is still of interest for comparative purposes.

Figure 5 shows the maneuver classification of 2,000,000 tracks sampled directly from our model into the nine vertical maneuver categories used in the European model.

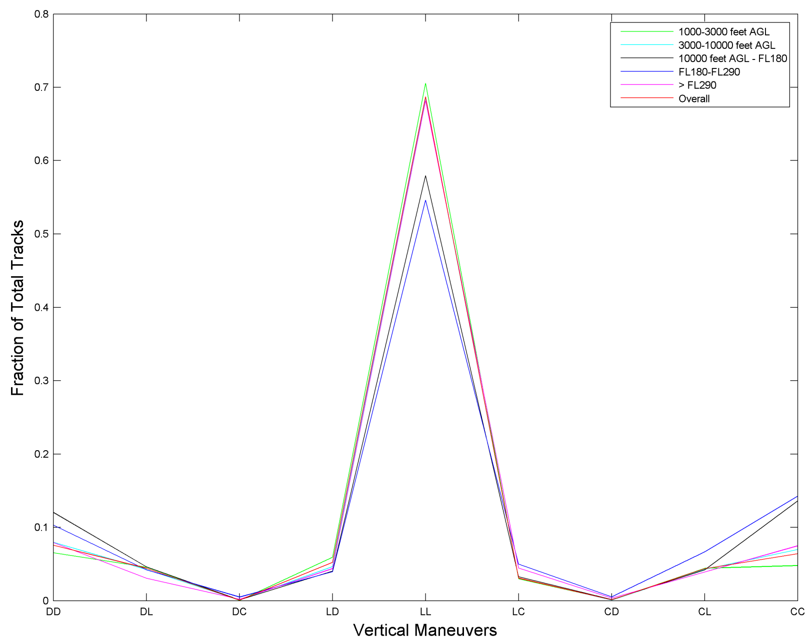

Figure 5. Vertical maneuver distribution of 2,000,000 directly sampled tracks from correlated encounter model.

The U.S. encounter model produces Level tracks between 60% and 75% of the time, depending on the altitude layer, with the rest spread out over the rest of the maneuver categories. The European encounter model, however, produces Level tracks only between 35% and 55% of the time (distribution not shown) [10]. Encounters in the U.S. are far more likely to involve one or both aircraft in Level flight than in the European model.

As will be explained in Section 4 of this report, the FAA has recently set up a monitoring capability at the nation's busiest terminal areas to capture RA downlinks from actual TCAS units. This downlink data was unavailable at the time of the construction of the U.S. correlated encounter model, but it will be incorporated in future updates to the model. The filtering process used to capture the 393,077 encounters used to build U.S. correlated encounter model was meant to roughly approximate the RA declaration logic found in TCAS. By way of validation that the model filter was capturing representative TCAS encounters, we classified the vertical maneuvers of aircraft involved in actual RAs from our current TRAMS dataset (described in Appendix B) representing a total of 10,702 tracks. The classification results are in Figure 6.

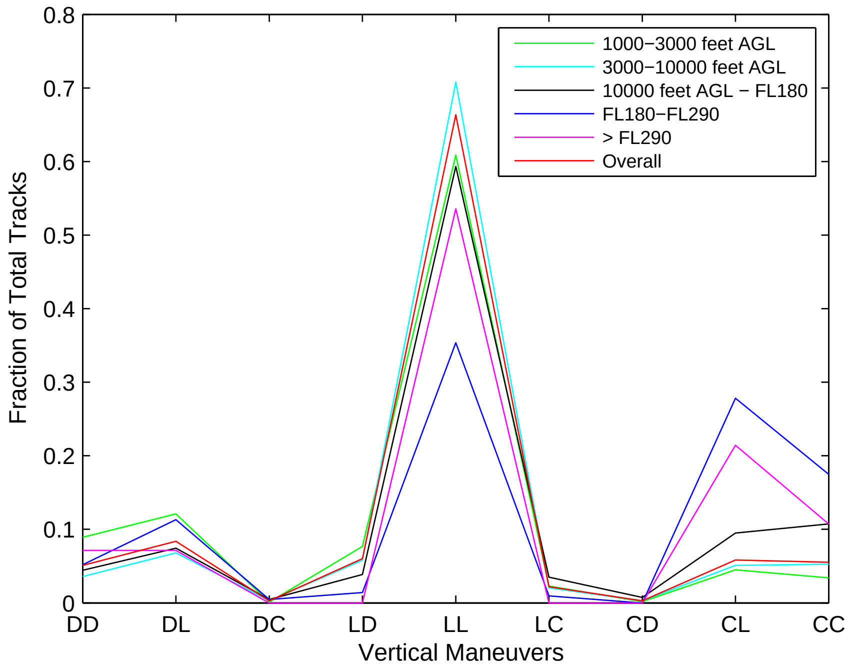

Figure 6. Vertical maneuver distribution of 10702 tracks from observed encounters involving an RA downlink from TRAMS dataset.

Note that TRAMS data is currently limited to busy terminal areas, whereas the dataset used for building the model includes many en route sensors and therefore many more flight hours in non-terminal airspace. Between 60% and 70% of tracks captured by TRAMS below FL180 are involved in Level flight. These results are similar to the maneuver distributions in samples created from the U.S. correlated encounter model. There were very few encounters from the TRAMS data in the uppermost altitude layers. Intuitively, however, the airspace around busy terminals would tend to include more aircraft in flight level transition in those layers than in en route airspace.

The difference in the distribution of maneuver types between the European model and the U.S. correlated model is a significant one, and has an effect on risk ratio. TCAS includes an on-board altitude tracker that attempts to estimate the current and future altitude of both ownship and the threat aircraft. Although the altitude tracker has been extensively tested, it is subject to estimation errors due to sudden vertical maneuvering and sensor measurement quantization, especially the intruder aircraft's vertical position [3]. It follows, then, that it is more difficult for TCAS to resolve conflicts with threat aircraft involved in vertical maneuvers than with threat aircraft flying level. The fact that the European model includes many more aircraft involved in vertical maneuvers indicates a more challenging environment for TCAS than what is observed and modeled in the United States. These issues were also mentioned in DO-298 in Appendix E.

As an additional comparison, Table 7 shows the risk ratios for V7.0 vs. Unequipped-intruder encounters (from the new correlated encounter model) with threat trajectories involved in the encounters classified as either level or non-level.

TABLE 7

Risk ratios (probability) for V7.0 (standard response) versus unequipped-intruder encounters by threat aircraft vertical profile type.

Level	Non-Level
10.81% (0.70)	16.10% (0.30)

3.1.3 Encounter Rate

Another major difference between the U.S. correlated encounter model and the European model used in DO-298 is the higher baseline encounter rate that has been observed in the U.S. The encounter rate in the United States is 0.0163 encounters/fl.hr. averaged over all altitudes and airspaces, or one encounter every 61.3 flight hours. By comparison, the encounter rate observed in European studies was 0.0023 encounters/fl.hr., or one encounter every 431.5 flight hours [1]. The encounter rate in the United States is 7 times higher than what was observed in European airspace during creation of the European model.

Most of the difference in encounter rates may be due to the fact that there is a higher density of aircraft in the United States than in Europe. There were 24,055,000 total flight hours observed in the United States during the nine month collection period for the correlated encounter model. If the area of the United States (as an estimate of the area of radar coverage) is approximately 4,365,000 NM^2, that implies a density of approximately $11.5 \cdot 10^4 \, \frac{\text{fl.hr.}}{\text{hr}\cdot\text{NM}^2}$. The European model included 1,030,000 total flight hours during a collection period of 9,281 hours [1]. The coverage area was approximately the size of France, which is 348,000 NM^2. Therefore, the European density was roughly $3.5 \cdot 10^4 \, \frac{\text{fl.hr.}}{\text{hr}\cdot\text{NM}^2}$. Although these estimates of density are approximate, it is likely that the aircraft density of the United States during the collection period for the correlated model was higher than the aircraft density observed during the collection for the European model. This is an important point, because, all other things being equal, a higher aircraft density will likely result in a higher encounter rate.

A higher encounter rate in the United States may also be a function of different airspace structure and ATC procedures. For example, in U.S. airspace, aircraft on Instrument Flight Rules (IFR) flight plans are allowed to assume visual separation responsibility in Visual Meteorological Conditions (VMC), especially during climb-out and descent in the terminal airspace. This is not allowed in Europe, and may result in aircraft flying closer together, but still operating safely. The effect of these rules would most likely show up in the lower altitude layers, especially under 10,000 ft

MSL, due to the high number of VFR aircraft and the effect of busy terminal airspace close to the surface.

The distribution of encounters over altitude layer for the U.S. correlated model is shown in Figure 7. The figure indicates that just over 90% of encounters in the correlated model occur in altitude layers 1 and 2, corresponding to between 1,000 ft AGL and 10,000 ft MSL. By comparison, in the European model, only about 60% of encounters occur in altitude layers 1 and 2. Although altitude layer definitions, shown in Table 8, are not exactly the same between the two models, for purposes of comparison they are approximately equal. The airspace structure, however, is significantly different between the United States and Europe.

TABLE 8

Altitude layer definitions for the European and U.S. correlated encounter models.

	U.S. Correlated	European
Layer 1	1000-3000 ft AGL	1000-5000 ft AGL
Layer 2	3000-10000 ft AGL	5000 ft AGL - FL115
Layer 3	10000 ft AGL - FL180	FL115 - FL195
Layer 4	FL180 - FL290	FL195 - FL295
Layer 5	above FL290	FL295 - FL495

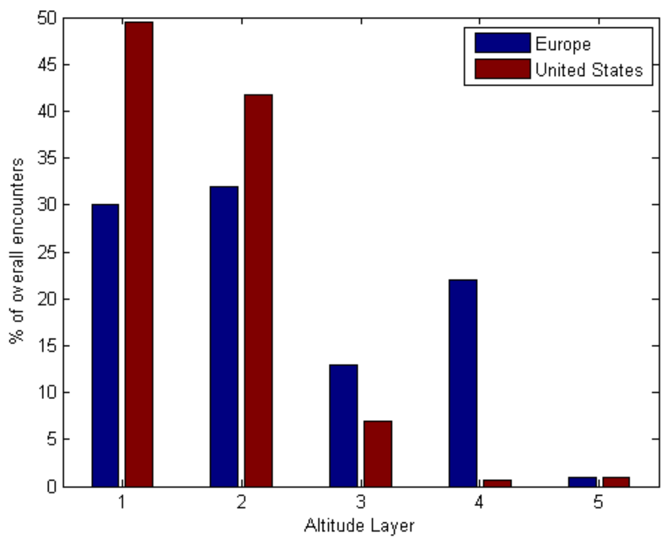

Figure 7. Altitude layer distribution for U.S. encounter model.

One way to look at the airspace structure of the United States is by looking at the airspace immediately surrounding airports, typically classified as Class B, C, or D airspace. Class B airspace typically surrounds the major airports, and can from 10-20 NM from the runways. Class C and D airspace are for minor airports, and generally have a radius of 5-10 NM. At low altitude (under 10,000 ft MSL), airspace that is not Class B, C, or D will typically be Class E airspace. Figure 8 shows the distribution of encounters for altitude layers 1 and 2 over the types of airspace included in our model.

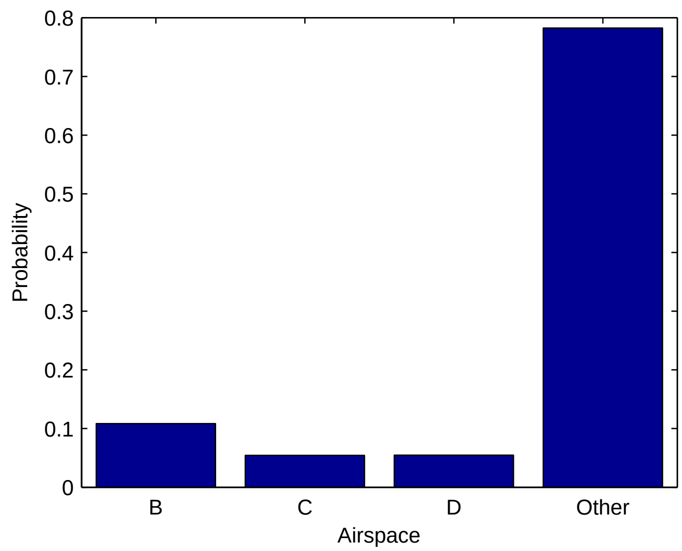

Figure 8. Airspace distribution for U.S. encounter model in altitude layer 1 and 2.

Approximately 80% of the encounters at low altitude (and therefore approximately 72% of encounters overall) in the United States occur in airspace other than class B, C, or D airspace, which means that most occur in Class E airspace. By comparison, approximately half of the total number of flight hours observed for the correlated model occurred in Class A airspace, but it included only 1% of the total number of encounters. Because no ATC clearance or radio communication is required for VFR flight in Class E airspace, the relatively high rate of VFR flight in the United States, as compared to Europe, may significantly contribute to the high encounter rate in this airspace class.

Figure 9 shows a histogram of observed encounters by aircraft flight rules and altitude layer. In altitude layer 1 (1,000 ft AGL to 3,000 ft AGL), the number of encounters with VFR aircraft are approximately double that of IFR encounters, similar to what was observed in Europe. A major difference between the United States and Europe, however, is in altitude layer 2, corresponding to between 3,000 ft AGL and 10,000 ft MSL in the U.S. correlated model, and between 5000 ft MSL and 11,500 ft MSL in the European model. In the United States, VFR and IFR encounters are equally likely in altitude layer 2, whereas in Europe, only about 15% involve VFR aircraft [10]. Higher levels of VFR traffic in the United States contribute to a greater number of IFR-VFR encounters in lower altitude layers, especially in altitude layer 2.

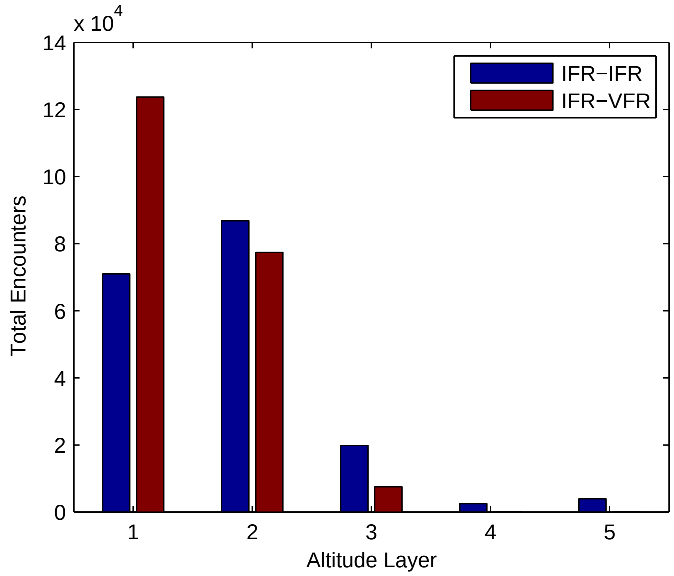

Figure 9. Types of flight involved in the observed U.S. encounters. VFR-VFR encounters were excluded.

Further research into the encounter rate in the United States is ongoing. The encounter rate in the United States is of potential concern because the probability of NMAC without TCAS is 0.0030, slightly higher than the probability of NMAC without TCAS from the European model (0.0028). Since the baseline encounter rate is about 7 times higher, the NMAC rate is also about 7 times higher in the United States than in Europe. However, jet transport aircraft flying principally between Class B, C, and D airports would have a significantly lower exposure to encounters than other IFR traffic flying in Class E airspace, and their expected NMAC rate would also be correspondingly lower.

3.2 COMPARISON TO RESULTS FROM PREVIOUS U.S. MODEL

The most recent prior encounter model developed specifically for the United States was a model developed by MITRE Corp. in 1984 and updated in the early 1990s [9]. This model was based on radar data collected from 12 sites across the United States and was two-dimensional, modeling only vertical motion of the aircraft. There have been significant changes in the U.S. airspace since the last U.S. encounter model was created, including the rise of regional jet fleets, the use of reduced vertical separation at higher altitudes, and increased traffic densities.

3.2.1 Risk Ratios

DO-298 contained risk ratios using the MITRE model in Monte Carlo simulation. Some of the results are reproduced here in Table 9 and Table 10. These tables are drawn from Table 6-1 and Table 6-2 in DO-298 respectively.

TABLE 9

Risk ratios for TCAS-TCAS encounters using the MITRE U.S. encounter model (25 ft quantization) [3].

	Equipage		
Pilot Response Model	V7.0 – V7.0	V7.0 – V7.1	V7.1 – V7.1
Standard–Standard	2.3%	2.3%	2.3%
Standard–No Response	9.0%	8.8%	7.7%

TABLE 10

Risk ratios for TCAS versus unequipped-intruder encounters (standard pilot response model) using the MITRE U.S. encounter model (100 ft quantization) [3].

Version 7.0	9.3%
Version 7.1	9.8%

For encounters with equipped intruders under standard response conditions, the risk ratios using the 2008 U.S. correlated encounter model (Table 1) are slightly lower than when using the MITRE model (Table 9). For encounters with non-responding and unequipped intruders, the risk ratios using the U.S. correlated model (Table 2) are slightly higher than when using the MITRE model (Table 10). In addition, whereas upgrading to V7.1 resulted in an increase in risk ratio against unequipped intruders using the MITRE model, we found a decrease in risk ratio using the U.S. correlated encounter model, similar to results from several other models in DO-298. Still, by way of comparison, the risk ratios from the new U.S. correlated encounter model are closer in value to the older U.S. model created by MITRE than they are to the more current European model.

4. CP-115 ANALYSIS

4.1 PURPOSE

As part of the analysis for CP-115, a study by Eurocontrol attempted to quantify the impact of this change in the logic not only in terms of the increase or decrease of separation between the two aircraft involved in an encounter, but also in terms of potential conflict with third party aircraft. Eurocontrol was tasked with the initial analysis, while the FAA provided surveillance data from high density terminal areas including the Boston, MA area and the New York, NY area. The study concluded that CP-115 did not cause any additional safety hazards— it neither reduced the safety of the encounter itself, nor induced any potential conflict with third party aircraft [2].

Recently, the FAA began fielding TRAMS at surveillance radar locations across the United States in high density terminal areas. In anticipation of TCAS RA Monitoring System (TRAMS) installations across the country, and to validate the results achieved by Eurocontrol, MIT Lincoln Laboratory was tasked by the FAA to develop a tool for analyzing CP-115 in much the same way as Eurocontrol, but with data from several TRAMS locations including Boston, MA, New York, NY and Los Angeles, CA. Similar tools will be deployed in connection with TRAMS to support future studies analyzing the compatibility between TCAS and anticipated NextGen procedures and technology.

This section describes preliminary results from our analysis tool using the same Boston, MA data supplied to Eurocontrol for their study in 2007, as well as more recent additional data. Three other sites, at PHL, JFK and LAX, have recently begun producing data, and the same process described in this report will be used to analyze the impact of CP-115 in those terminal areas in a future study. Section 4.2 describes our methods and data sources. Section 4.3 describes our analysis results.

4.2 METHODS

The process to evaluate the effect of CP-115 on safety is to (1) collect actual surveillance data (including RA downlinks), (2) filter the data to identify tracks involved in encounters in which an AVSA was issued, and (3) recreate those encounters in simulation to study what happens if the AVSA is changed to a LOLO. We then analyze the results of the change in simulation, and compare the simulation results to what we actually observed.

4.2.1 Data

Our radar data comes from the Mode S Evaluation Facility (MODSEF) sensor at MIT Lincoln Laboratory located in Lexington, Massachusetts. MODSEF is a production quality Mode S sensor that has a 60 NM detection range, and has a scan period of 4.6 s. MODSEF also interrogates any TCAS units in its coverage region on the 1030 MHz frequency, and receives downlink replies from TCAS equipped aircraft at 1090 MHz. Downlink replies include the register contents of TCAS at the time of interrogation, used to determine the RA issued and the Mode S address of the threat aircraft (if available), as well as the Mode S address of the aircraft on which the TCAS unit is installed. MODSEF also includes a secondary surveillance radar (SSR) which provides surveillance information on aircraft including range, azimuth and (when available) altimetry information for every scan.

Our data includes tracked beacon reports between March 1, 2006 and July 31, 2006 and between July 1, 2007 and June 31, 2008, representing a total of 16 months of data. The 2006 data was the same data provided to Eurocontrol for the original CP-115 study.

4.2.2 Filtering and Data Processing

The filtering and data processing performed on the data is described in Appendix B. However, since the data is from the MODSEF facility, it does not go through the DRUFF processing stage that all TRAMS data must go through.

The interpolated track positions and extracted control features ($\dot{h}$, $\dot{\psi}$, $\dot{v}$) are input into the simulation to recreate the observed encounter. Our simulation environment is described in Appendix A.

4.3 RESULTS

The results in this analysis are based on 518 encounters observed from the ASR-9 in Lexington, MA (near Bedford airport / Hanscom AFB) that occurred over two periods of observation between March 2006 and June 2008 and resulted in an AVSA RA (see Figure 10). AVSA encounters represent 15.1% of all observed encounters in the Boston terminal area.

Figure 11 presents the location of the aircraft at time of closest approach (TCA) for all 518 AVSA encounters and indicates the number of third party aircraft in the local vicinity of encounter. The definition of third party aircraft is quite broad; as detailed in Appendix B, a third party aircraft can be as far as 10 NM and 10,000 ft away from the encounter in range and vertical separation respectively. A number of encounters occur south of Boston Logan International Airport, which likely correspond to RAs issued during parallel runway operations. The two distinct lines of RA events west of Bedford coincide with standard approach paths into Logan. Finally, a majority of scattered encounters over the Bedford airport are likely due to the proximity of aircraft in the traffic pattern with other aircraft.

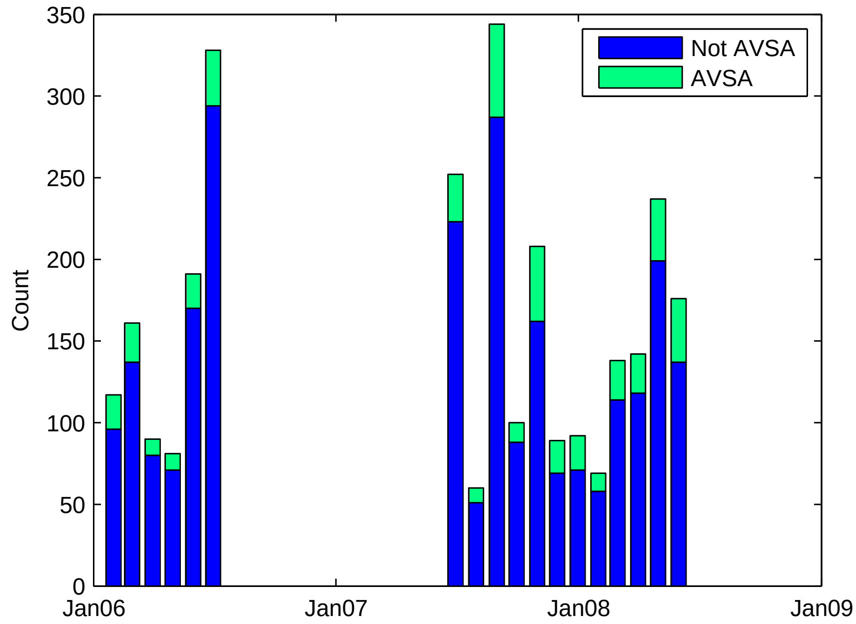

Figure 10. Encounter timeline.

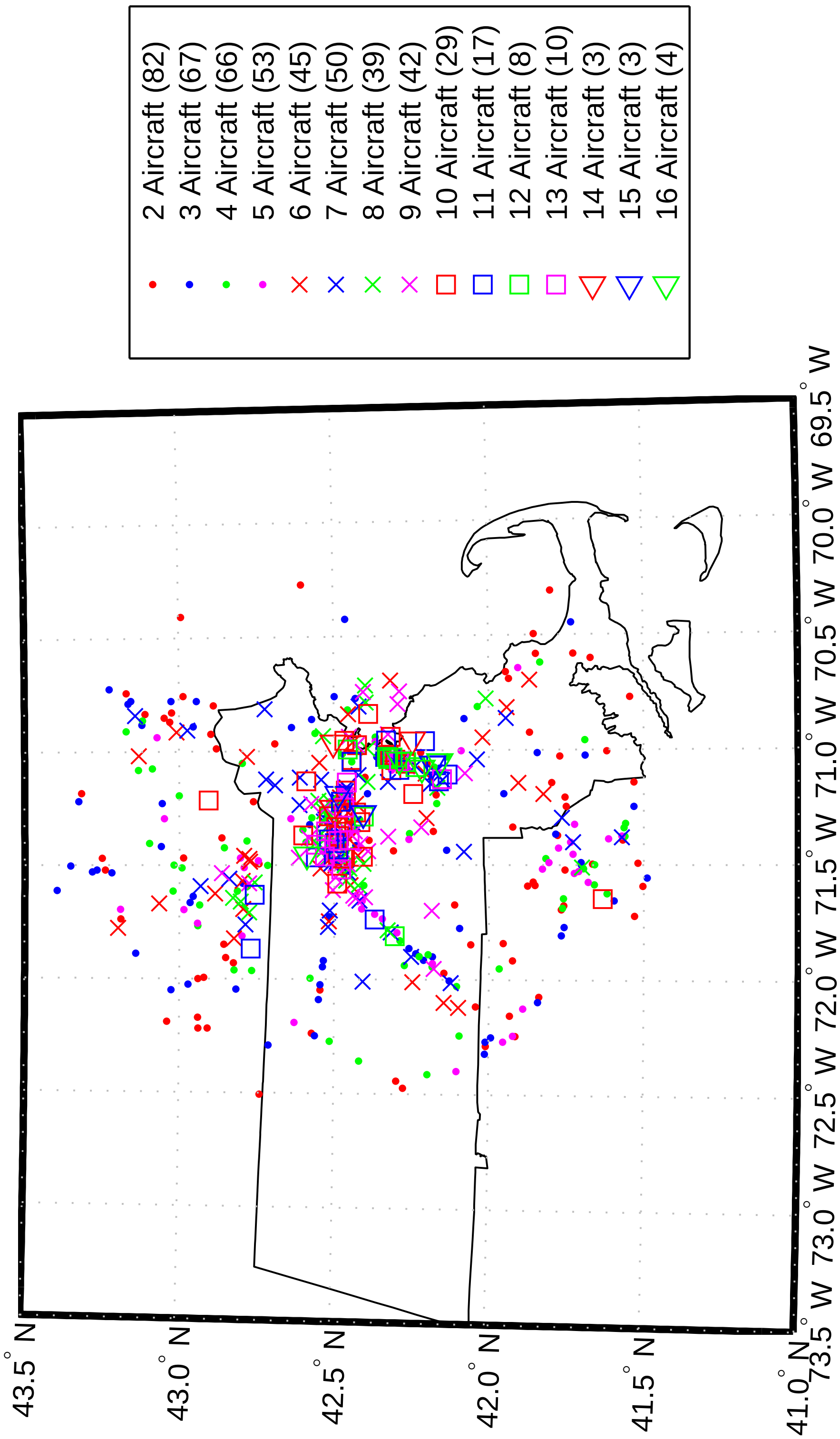

Figure 11. Location of AVSA encounters.

4.3.1 Resolution Advisory Replication

In order to evaluate RA replication accuracy, we looked at three criteria: (1) how often we generate any RA in simulation with the primary intruder aircraft, (2) the time that the RA begins in simulation relative to the time of the first downlink, and (3) the values in the MB subfields for the first downlink RA and first simulated RA.[1]

Generated Resolution Advisories

We simulated each encounter 5 times since some encounters only result in an RA a fraction of the simulated encounters due to variances in sensor noise and altimeter error models. Results in this section are based only on the smoothed radar tracks; currently, tracks are not jittered to replicate RAs. Note that we anticipate jittering of the tracks in the future will result in a higher percentage of encounters being replicated in simulation. Table 11 presents data showing how often (out of 5 encounters) that we generated an RA in simulation with the primary intruder aircraft for all AVSA encounters. Approximately 43% of encounters always resulted in a generated RA, 5% some portion of the time, and 52% of the encounters never generated an RA in simulation. Note that an additional 25 of the 518 AVSA encounters, not presented in Table 11, lacked sufficient data to recreate the encounter for simulation (e.g., less than 10 surveillance reports from one or more of the threat aircraft).

TABLE 11

Times an RA is generated out of five simulated encounters.

Number of encounters	5	4	3	2	1	0
	214	9	7	3	6	254

Time of First Resolution Advisories

Figure 12 shows the time of the first issued RA in simulation relative to the timing of the RA in the downlink for encounters that generated an RA in simulation. Note that 45% of those simulated encounters generated the first RA within 5 seconds of the first downlink. Because the radar only interrogates each aircraft once approximately every 5 seconds, we can only estimate the true time that the RA was generated in the actual encounter within the one radar scan (5 seconds) before the recorded time of the downlink. Thus, simulated RAs in the green region are considered to match the time of the downlinked RA. A further 33% of simulated encounters result in an RA within plus or minus one scan of the observed downlink.

MB Subfields

We compare the type of initial RA from the downlink and generated in simulation using three

[1]The MB subfield is part of the downlink message which contains a description of the RA that was issued by TCAS [11]

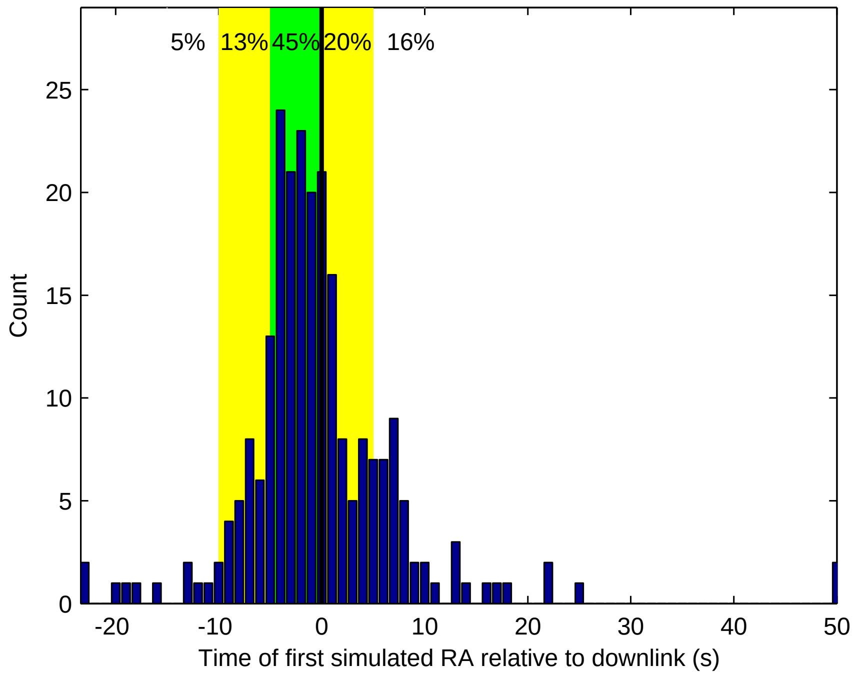

Figure 12. Statistics on timing of first RA in simulation.

features from the MB subfields:

Bit 42 RA type specifying either corrective or preventative.

Bit 43 RA sense specifying either an upward or downward advisory.

Bit 47 Specifying that the RA is either a vertical speed limit or positive.

In the 239 encounters that generated an RA, 130 matched all 3 features, 74 matched 2 features, 34 matched 1 feature, and a single encounter did not match any of the features.

These results suggest that without jittering of the aircraft tracks we are able to replicate approximately one fourth of all initial RAs: approximately half of the simulated AVSA encounters generated an RA; out of those encounters, approximately one half of the generated RAs match all of MB subfields in the downlink and occur within one radar scan of the time recorded for the first RA in the downlink.

Figure 13 shows the numbers achieved from each stage of processing. In our data set, 15% of encounters involve an AVSA but only 25% of AVSA encounters would be affected by CP-115. These numbers imply that approximately 3.7% of RAs in the Boston airspace would be affected by CP-115. Furthermore, only around two-thirds of those encounters have any third party aircraft in the vicinity at the time of the RA.

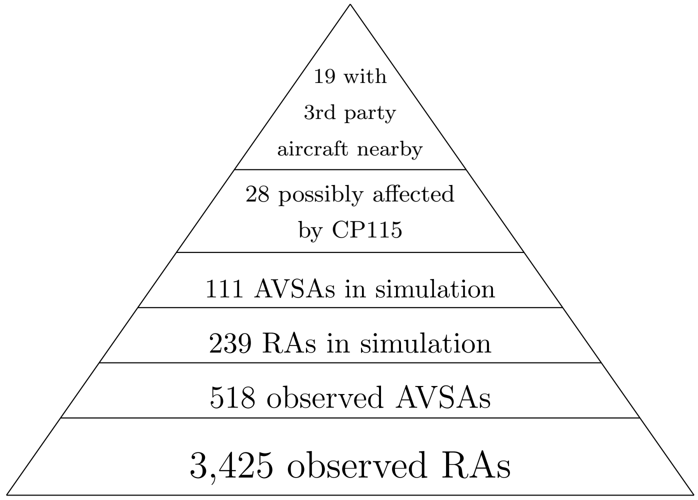

Figure 13. The number of encounters after each stage of processing.

4.3.2 Breakdoown of AVSA Resolution Advisories

Out of the 518 observed AVSA encounters, 111 of them generated an AVSA in simulation. Figure 14 shows the break down of AVSA RAs that were generated in simulation with TCAS version 7. Encounters that result in a "Do Not Descend" or "Do Not Climb" RA will not be affected by CP-115. The encounters that will be affected by CP-115 are the vertical rate magnitude reduction RAs including the limit climb or limit descend RAs; for instance, in Figure 14, "LC500" indicates an RA to limit the climb to 500 ft/min. Only 28 of the 111 simulated AVSA encounters will be affected by CP-115. Furthermore, only 19 of those encounters involved more than two aircraft—we investigate the effect of CP-115 with third party aircraft for these encounters in Section 4.3.4.

4.3.3 Threat Aircraft Results

We use VMD as a metric to compare TCAS V7.0 against TCAS V7.1. In this analysis we define VMD as the vertical separation between two aircraft at TMCD. Our definition of TMCD is related to the definition of an NMAC, a loss of 100 ft vertical separation and 500 ft horizontal separation. We define TMCD to be when the following metric is minimal:

$$m(t) = \max\left(\sqrt{(x_1(t) - x_2(t))^2 + (y_1(t) - y_2(t))^2}/5, |h_1(t) - h_2(t)|\right)$$

where $(x_1(t), y_1(t), h_1(t))$ and $(x_2(t), y_2(t), h_2(t))$ are the three-dimensional coordinates of the two aircraft involved in the encounter. This metric balances horizontal and vertical separation. Figure 15 is a contour plot of $m(t)$, showing where $m(t)$ is of constant value.

Intuitively, TMCD is the instance when two aircraft are of greatest threat to each other. TMCD is used as a surrogate for TCA to correct for the fact that smaller vertical miss distances are acceptable relative to lateral distances. TMCD should more accurately capture that most dangerous point of separation between the two aircraft.

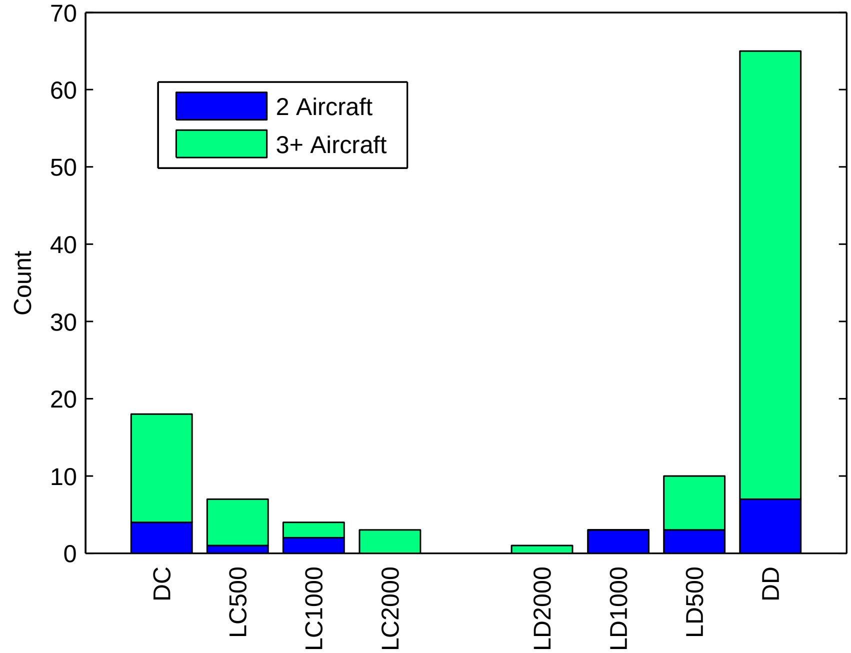

Figure 14. AVSA types.

Figure 16 shows how both V7.0 and V7.1 increase vertical separation from the threat aircraft in the majority of the 28 encounters we were able to simulate that would be affected by CP-115. The green dots in the graph represent encounters in which a standard response to TCAS would have increased vertical separation at TMCD versus what was observed. The red dots represent encounters where a standard TCAS response would have decreased vertical separation versus what was observed. Black dots represent equivalent separation. Standard responses to TCAS increases separation in many observed encounters, but in some cases the pilots reacted appropriately, and occasionally perhaps over-reacted.

Figure 17 shows that V7.1 increases vertical separation with the threat aircraft more than V7.0. In fact, in all but one of the encounters we looked at, V7.1 either increases or does not change vertical separation at TMCD. The one encounter in which VMD is decreased, it is only decreased by approximately 50 ft.

4.3.4 Third Party Aircraft Results

There are a total of 49 third party aircraft in the 28 AVSA encounters that could be affected by CP-115. No RAs are issued in simulation with third party aircraft when the own aircraft is equipped with either V7.0 or V7.1. Figure 18 shows range and vertical separation for third party aircraft at TMCD between the own aircraft and the primary intruder aircraft. No third party aircraft are within 2 NM and 2000 ft of the own aircraft at TMCD. Almost an equal number of third party aircraft are in each of the four combinations of relative range and altitude rate. We

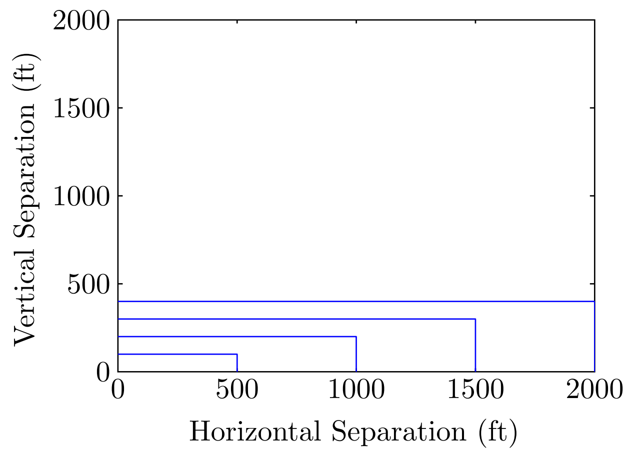

Figure 15. TMCD metric. Illustrated are contours of constant value.

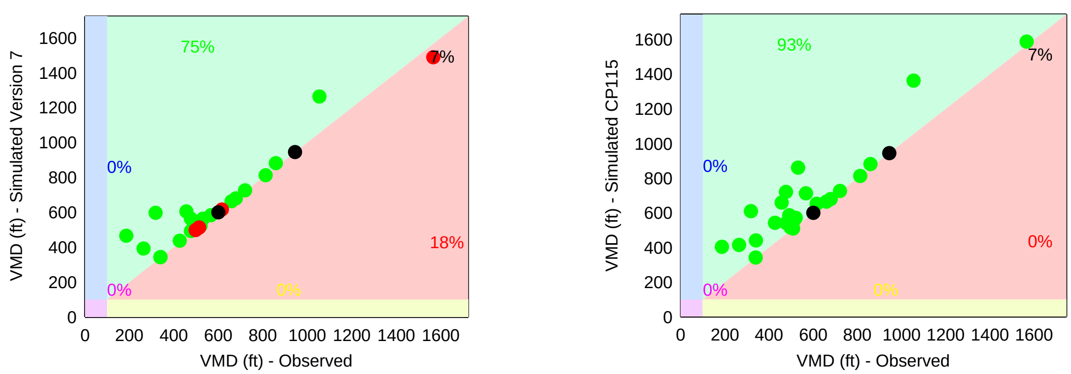

Figure 16. Observed VMD versus simulated VMD for V7.0 and V7.1.

take a closer look at those aircraft whose range is converging, because these aircraft represent the greatest potential threat.

Figure 19 shows estimated time until minimum separation (τ) and the projected vertical separation for third party aircraft where $\tau \leq 300\,s$. The minimum τ value is 42 s for which the projected vertical separation is around 3500 ft. On the basis of this figure, it is unlikely that a response to an RA issued by V7.1 would cause any potential safety concern with third party traffic in the Boston airspace.

Figure 20 shows minimum cylindrical distance (MCD) between the own aircraft and third party aircraft at TMCD with both TCAS V7.0 and TCAS V7.1. In our simulations, V7.1 actually increases separation, either laterally or vertically, with third party aircraft over V7.0 in 39% of cases. In 41% of cases, the separation does not change. In the remaining 20% of cases, the decrease in separation is minimal. It can be seen from the plotted points in Figure 20 that in cases where third party aircraft are within about 4000 ft vertically or 3.5 NM horizontally, separation is either unaffected or increases with V7.1. These results suggests that CP-115 actually increases separation

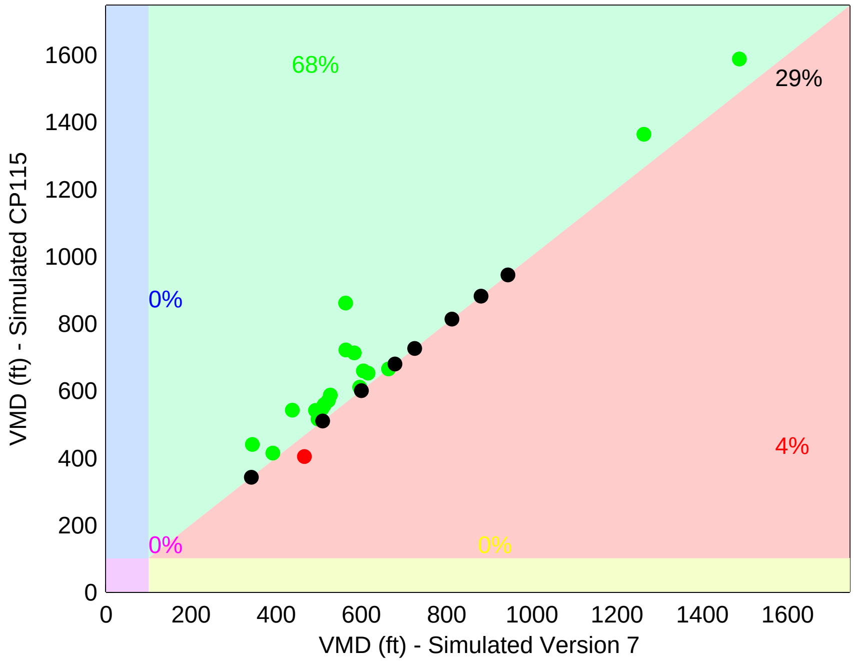

Figure 17. Simulated VMD for TCAS V7.0 versus simulated VMD for TCAS V7.1.

with third party aircraft, which is contradictory to initial concerns over CP-115.

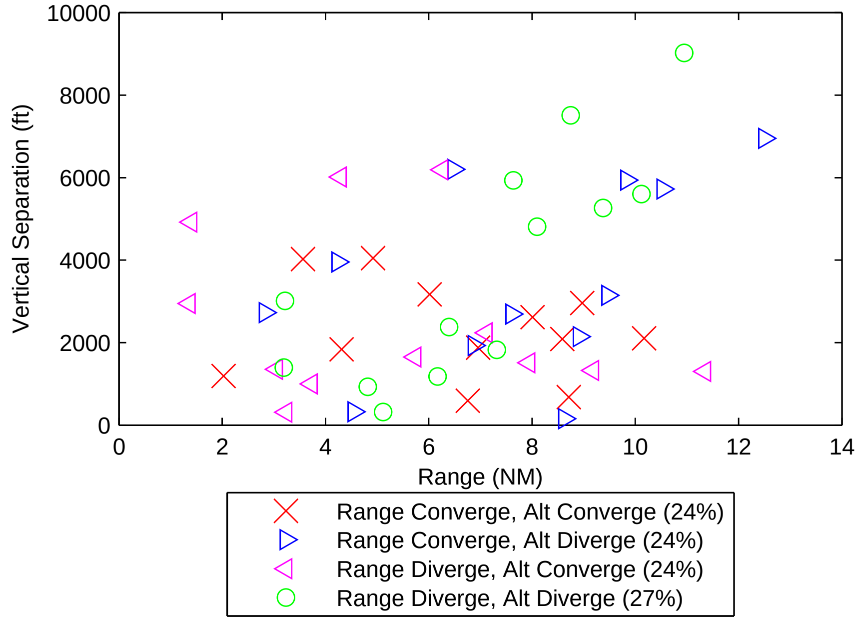

Figure 18. Range versus vertical separation for third party aircraft relative to the own aircraft observed at TMCD between the primary aircraft. The markers indicate whether traffic is converging or diverging in both range and altitude.

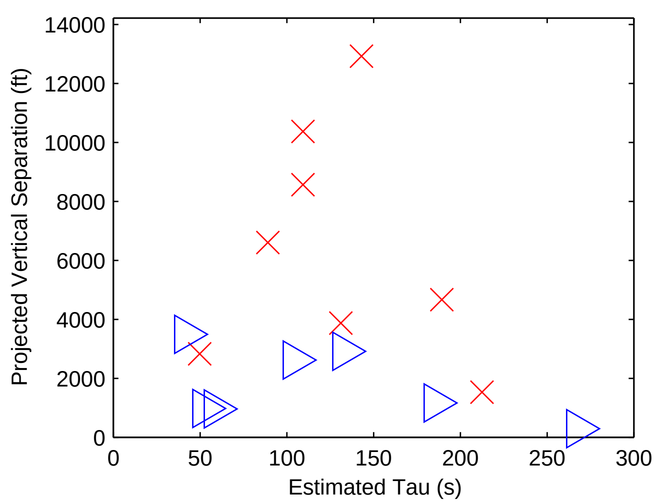

Figure 19. Estimated Tau and projected vertical separation for third party aircraft with converging range.

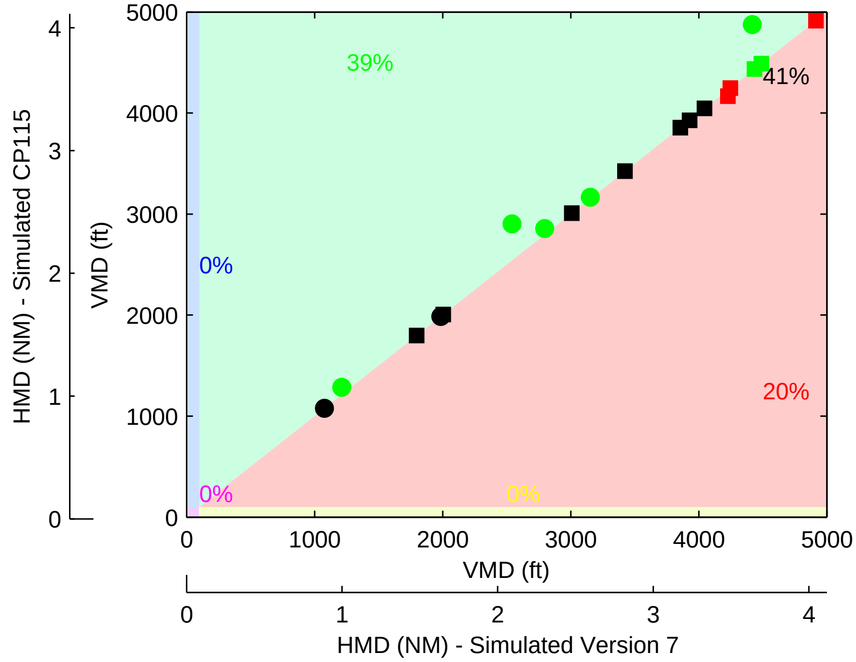

Figure 20. Miss distance for third party aircraft: V7.0 versus V7.1. In this figure a circle denotes that the vertical separation between the two aircraft maximizes the equation for MCD, whereas a square means the horizontal separation maximizes MCD. Circle positions are thus read off of the VMD axes, while square positions are read off of the HMD axes. Only shown are third party aircraft within 5000 ft or 4 NM, but the percentages in the figure are for all third party aircraft.

4.4 SUMMARY

Our study found 15.1% of encounters involve an AVSA, whereas Eurocontrol had a slightly lower estimate of 9.2%. Furthermore, only 17% of AVSAs would be affected by CP-115 with third party traffic in the area, whereas Eurocontrol had a slightly higher estimate of 21%. In general, however, these percentages are approximately the same given the fact that we used different data for our analysis.

Our study of V7.1 supports the conclusions drawn by Eurocontrol in 2007; in summary, we found:

- Exposure to encounters that would be affected by CP-115 is low (in our study around 3.7% of RAs).
- V7.1 increases separation with the intruder aircraft.
- V7.1 also generally increases separation with third party aircraft, through there is no algorithmic consideration that should always lead to this result.
- V7.1 did not induce any additional RAs with third party aircraft in our analysis.

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5. CONCLUSIONS

This study confirmed the results documented in DO-298 regarding the benefit of CP-112E. Furthermore, this study found no additional risk in upgrading TCAS to V7.1 (including both CP-112E and CP-115), coupled with major risk reductions in cases with non-responding intruders equipped with TCAS. The impact of the new U.S. correlated model is still under investigation, but preliminary results indicate a higher positive safety impact of TCAS in the United States than in Europe due to the different types of encounter situations observed. This impact attains greater significance in light of the fact that the overall encounter rate (and, concurrently, the NMAC rate) in the U.S. appears to be significantly higher than the rate observed in Europe. Some caution is required in interpreting these NMAC rates, however, because the exposure of transport aircraft to encounters is expected to be significantly lower than the general traffic population.

In addition, the results from a simulation analysis of the Boston terminal airspace indicates that V7.1 tends to increase vertical separation with intruder aircraft without inducing any RAs against third party aircraft. The results are similar to those previously documented. The simulation techniques developed at Lincoln Laboratory are appropriate to conduct further studies into this matter for other terminal airspaces under surveillance by the TRAMS program.

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APPENDIX A
CASSATT

The Collision Avoidance System Safety Assessment Tool (CASSATT) performs fast-time Monte Carlo analysis of aircraft encounters. CASSATT takes either real radar tracks or encounter model data, such as the current US encounter model being developed at Lincoln Laboratory, as an input and simulates aircraft motion over a period on the order of one minute near the closest point of approach between two or more aircraft. The simulation is developed in MATLAB and has several integrated sub-models including TCAS, sense-and-avoid sensor models and algorithm logic, 3-dimensional airframe models, a human visual acquisition model, a pilot response model, command and control latency, and an adjustable vehicle dynamics model. Aircraft motion is represented using 6 or 4 degree-of-freedom (DOF) point-mass dynamics with acceleration constraints and transient response characteristics related to aircraft type.

This section presents a high-level overview of CASSATT. First, this section describes analyses performed with CASSATT and recent developments of the simulation tool. Next, this section describes the various sub-models in CASSATT, which can be thought to be made up of outer-loop and inner-loop components. The dynamic model (inner-loop) defines how the aircraft interact with each other and simulates details every tenth of a second. The outer-loop defines how aircraft encounter each other in the simulation and may be derived from an encounter model or from real radar tracks.

A.1 SIMULATION ANALYSIS AND DEVELOPMENT

Lincoln Laboratory has been involved in TCAS development since it's beginning in the 1970s when the FAA tasked Lincoln Laboratory with developing the surveillance subsystem for TCAS. After TCAS was deployed, Lincoln Laboratory continued its involvement with TCAS by monitoring aircraft equipped with TCAS in the Boston airspace. The Laboratory then began assessing the threat logic in TCAS in the mid-1990s. This effort required the development of simulation and analysis tools that eventually evolved into what is now known as CASSATT.

In collaboration with several other organizations such as MITRE, Lincoln Laboratory used CASSATT to analyze the safety of a proposed change to the TCAS resolution advisory reversal logic. This analysis led to the FAA's acceptance of the changes proposed in 2005.

In 2006 Lincoln used CASSATT to provide feedback of TCAS performance on the U.S. Air Force's Global Hawk unmanned aircraft. Results from this study provided estimates on the effects of increasing control and communication latencies in response to a TCAS RA on Global Hawk.

More recently the FAA has expressed interest in Lincoln Laboratory expanding CASSATT for more complex studies such as analyzing TCAS performance with multiple intruders and simulating actual TCAS encounters that have been observed in the United States. CASSATT is now capable of flying up to 10 aircraft in a single encounter scenario. Two of the aircraft may be equipped with TCAS and are capable of responding to an RA.

A.2 DYNAMIC MODELING

The CASSATT simulation environment utilizes several integrated sub-models such as an aircraft dynamic model, TCAS, and pilot response and visual acquisition models. Sense and avoid sensor and noise models are also included:

Aircraft Aircraft dynamics are represented using a tunable 6 DOF or 4 DOF point-mass dynamic models, which includes aircraft transient response characteristics and performance limits such as maximum pitch rate or bank angle. Most of our analysis is based on a general aircraft dynamic model used for TCAS safety analysis; however, we use specific aircraft models when we anticipate the dynamics of a specific aircraft are important for the validity of our analysis.

The aircraft in CASSATT typically fly trajectories that are defined by an encounter model and based on aircraft turn rate, vertical rate, and airspeed acceleration. These control values may change every tenth of a second and may also be user-defined. CASSATT is also capable of flying aircraft along a specific track defined by x-, y-, and z-points. This capability may be used to fly actual encounters that have been observed in the airspace and captured by a radar sensor. This mode of flight may also be turned off at any arbitrary event in the simulation such as a TCAS RA and the aircraft will deviate from the specified track in response to the RA. We can then assess hypothetical situations such as the effect that a change in the TCAS code may have on the result of an encounter that we observed in our radar feed.

CASSATT uses a variety of 3-dimensional aircraft wire-frame models for pilot visual acquisition and sensor trade-off studies. A sample of the current models include an ultra-light, a Cessna 172, a Boeing 747 and Global Hawk.

TCAS A simulated aircraft in CASSATT may either be equipped with a Mode C transponder or a Mode S transponder without TCAS, with TCAS Version 7 or with TCAS Version 7 plus CP-112E and CP-115. Honeywell, A TCAS vendor, provided Lincoln Laboratory with their TCAS source code that we successfully integrated into CASSATT. The TCAS model can track up to 9 intruders, allowing us to simulate TCAS encounters involving up to 10 aircraft. CASSATT can currently model two of those aircraft as TCAS-equipped aircraft. However, CASSATT can be expanded to accommodate additional TCAS-equipped aircraft if it is necessary for a particular analysis.

Given the safety nature of analysis done with CASSATT, it is essential to ensure the validity of TCAS performance in the simulation. We validate TCAS behavior in CASSATT with a test suite provided by RTCA termed TSIM, which consists of several hundred scenarios that test the different components of the TCAS logic. The logic in the test suite is identical to that which may be found in actual aircraft. We generate similar results for both pairwise and multi-intruder encounters in CASSATT as is specified from the TSIM encounters.

Pilot The pilot model computes the appropriate acceleration commands for the aircraft dynamics based on information from visual acquisition and TCAS. The delay and strength of the pilot response are both tunable in CASSATT. The visual acquisition model in CASSATT is a probabilistic model based on flight tests from TCAS safety studies performed at Lincoln

Laboratory and is a function of the number of pilots in the cockpit, workload, the cockpit field-of-view, the size of the intruder aircraft, and range to the intruder.

A.3 ENCOUNTER MODELING

CASSATT may simulate encounter generated from an encounter model or from an encounter that was actually observed in the airspace.

The function of an encounter model is to generate random encounter situations between two aircraft that are representative of potentially hazardous events that may occur in the actual airspace. The encounters represented by the model are those involving aircraft in the final stages before a collision, typically over a period of time on the order of one minute or less. Several encounter models have been developed since the 1980s. CASSATT includes the ICAO and Eurocontrol encounter models, in addition to the the new U.S. encounter models being developed at Lincoln Laboratory.

Since aircraft tracks obtained from radar data include noise and data points only approximately every 5 s we preprocess the radar tracks before inputting them into CASSATT. First, we perform outlier detection and smooth the radar tracks. Next, we interpolate down to every tenth of a second (the rate of CASSATT) and extract control features such as turn rate, climb rate, and airspeed acceleration. This pre-processing allows us to simulate an aircraft in three distinct ways:

Open-Loop An aircraft may be initialized at the beginning of the simulation and then allowed to follow the commands that we extracted from the smoothed radar track. Since our aircraft control model includes basic aircraft constraints and dynamic response latencies, modeling an aircraft in this manner will lead to positional errors over time. This method is sufficient for short time periods less than a minute; however, can grow quickly for aircraft who are maneuvering often throughout the encounter.

Closed-Loop An aircraft that is simulated in closed-loop form is forced to follow the smoothed and interpolated radar track. This method ensures that no errors build up with time. However, the aircraft is not able to respond to a TCAS RA.

Hybrid An aircraft that is simulated in hybrid form is forced to follow the smoothed radar track until the time that an RA is issued. At that point in the simulation, the aircraft is switched over to open-loop mode and is allowed to respond to the RA as defined by the pilot model. This method of simulation is particularly useful if the RA occurs more than approximately one minute into the simulation.

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APPENDIX B
TRAMS

In 2008, the TCAS Program Office initiated the development of the TCAS Resolution Advisory Monitoring System, or TRAMS. The key piece of technology enabling TRAMS consists of a passive attachment to a Mode S surveillance radar which decodes and stores TCAS downlink transmissions that the radar receives over the 1090 MHz Mode S transponder datalink. This system is similar in function to the MIT Lincoln Laboratory MODe S Experimental Facility (MODSEF), which consists of a commercial grade Mode S terminal surveillance radar similarly capable of receiving TCAS downlinks and is located in Bedford, MA. Up until the implementation of TRAMS at the JFK International Airport in June, 2008, the MODSEF facility has been only facility for TCAS operational monitoring in the United States. Eventually, TRAMS will be installed at 32 sites around the United States, generally in high traffic density regions with many pilot reported resolution advisories.

B.1 TRAMS DATA PROCESSING

B.1.1 DRFF

Once the data has been collected at the sensor, a Data Reduction and Filter Function (DRFF) developed by the FAA William J. Hughes Technical Center filters the raw surveillance and downlink data and identifies the pair of tracks involved in an RA declaration, as well as third party tracks in the vicinity of the RA declaration. DRFF stores up to 20 minutes of surveillance data from each track pair involved in the encounter, and up to 7 minutes of surveillance data from each third party track, defined as tracks with horizontal separation less than 10 NM and vertical separation less than 10,000 ft from the TCAS aircraft during the time of the RA

The DRFF process also produces a track summary file which contains start and end times for each track observed by the sensor, whether or not they were involved in encounters, and a sensor summary file which contains summary statistics such as number of surveillance reports, number of tracks, and number of RA reports in order to produce rate statistics by flight hour. [12]

B.1.2 Filtering

In order to identify encounters from DRUFF data, we start with tracks associated with an RA. For each track associated with an RA, we then attempt to find the intruder most likely to have caused the RA according to the following two-step process:

1. Find all aircraft which violate protected space around the TCAS aircraft: defined as horizontal separation less than 2 NM and vertical separation less than Δh depending on the altitude of the TCAS aircraft according to Table B-1. This search is done only during the time of the RA.
2. If the first step found zero intruders, look for the aircraft within sensor coverage at the time of the RA that reached minimum slant separation from the TCAS aircraft during the RA. As

TABLE B-1

Δh values at various altitudes (units are feet).

Altitude	Δh
< 5000	300
$[5000, 10000)$	350
$[10000, 20000)$	400
$[20000, 42000)$	600
$>= 42000$	700

there is no limit on the separation distance, this step will always find an aircraft of interest as long as there are other tracks during the time of the RA.

Once an aircraft issuing an RA has been associated with an intruder aircraft(s), we then attempt to find all third party aircraft in the area. A third party aircraft is defined as an intruder with horizontal separation less than 10 NM and vertical separation less than 10,000 ft from the TCAS aircraft during the time of the RA.

B.1.3 Processing

The time-step for our simulation environment is 0.1 s, which is much smaller than the scan period of the surveillance radar. Thus, in order to prepare the observed encounters for simulation, we process the surveillance data to form high quality tracks.

For each track, we detect and remove outlier radar reports. In the horizontal plane, we remove jumps with ground speeds above 600 kt using the following algorithm. We begin by estimating the speed between each sample point by dividing the distance between samples by the time interval between samples. Samples on either side of segments where the speed is above the threshold of 600 kt are stored in a list of candidates for removal. We iterate through the list of candidates and remove the one that minimizes the sum of speeds above the set threshold. The process repeats until there are no longer any segments with speeds above the threshold. We then use the same process to remove points that have a turn rate magnitude greater than 8 deg/s, and acceleration greater than 3 kt/s^2 in magnitude. In the vertical plane, we remove missing Mode C altitude reports. Then we remove outliers with vertical rates greater than 5000 ft/min in magnitude.

After removing any outliers from a track, we smooth the remaining data points, first horizontally and then vertically. We use the same smoothing scheme for both horizontal and vertical smoothing. We use the following general formula to transform a raw trajectory $(t_1, \boldsymbol{x}_1), \ldots, (t_n, \boldsymbol{x}_n)$ to a smoothed trajectory $\boldsymbol{y}_1, \ldots, \boldsymbol{y}_n$.

$$\boldsymbol{y}_i = \frac{\sum_j w(t_i, t_j)\boldsymbol{x}_i}{\sum_j w(t_i, t_j)}, \tag{B-1}$$

where $w(t_i, t_j)$ is a weighting function that monotonically decreases as the difference between t_i

and t_j increases. For the weighting function, we use the following definition based on a Gaussian kernel with standard deviation σ,

$$w(t_i, t_j) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t_i - t_j)^2}{2\sigma^2}\right) . \quad \text{(B-2)}$$

When smoothing horizontally, we use $\sigma = 5\,\text{s}$. When smoothing vertically, we use $\sigma = 15\,\text{s}$. A larger σ is required for vertical smoothing because of 100 ft Mode C quantization.

Our smoothing parameters were chosen to balance the ability to extract meaningful features while still matching our observations in the presence of measurement error.

The time interval between radar scans in our data is much longer than the 0.1 s time step of our simulation - terminal surveillance radars scans aircraft approximately every 4.6 seconds. Additionally, it is common for the sensor to skip one or more consecutive scans of a target and some scans produce outliers that we remove. Hence, we interpolate to provide inputs to our simulation. We chose a piecewise-cubic Hermite interpolation scheme that preserves monotonicity and shape [13].

Using the interpolated plot positions, we calculate the control features used for simulation:

- **Vertical rate ($\dot{h}$):** The vertical rate is estimated from the smoothed and interpolated altitudes estimated from Mode C reports. The vertical rate at time t is given by $\dot{h}(t) = \frac{h(t+1)-h(t)}{\Delta t}$.
- **Turn rate ($\dot{\psi}$):** We first compute the heading along the interpolated track. The heading at time t is given by $\psi(t)$ and corresponds to the direction from $(x(t), y(t))$ to $(x(t+1), y(t+1))$. To compute the turn rate at time t, we find the acute change in heading between $\psi(t)$ and $\psi(t+1)$. Turns to the right have positive turn rates, and turns to the left have negative turn rates.
- **Acceleration ($\dot{v}$):** To find the acceleration at a particular point, we average the change in airspeed per unit time looking forward one time step and looking back one time step.

B.2 AVAILABLE TRAMS DATA

As of the writing of this report, Lincoln Laboratory has received data from TRAMS sensors for the months indicated in Table B-2.

Most months are incomplete, due to communication errors between the remote TRAMS sites and the central collection site located at the FAA Technical Center. However, the available data still contains 5351 high quality encounters from the sensors listed in Table B-2, and we have used information from these encounters in this report.

TABLE B-2

Months of received TRAMS data, 2008. Complete months are labeled with an "X," incomplete are labeled with an "I."

Sensor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
JFK						X	X			I	I	I
PHL					I	X	X			I	I	I
LAX											I	I
MODSEF	X	X	X	X	X	X						

APPENDIX C
IMPACT OF PSEUDOCODE CHANGE TO PREVENT GREEN-ARC-ON-WEAKING BEHAVIOR IN CASSATT

We implemented the proposed pseudocode change to prevent green-arc-on-weakening behavior into the TCAS version 7.1 code that we use in Lincoln Laboratory's CASSATT. Green-arc-on-weakening behavior is when RA weakening is due to a multiaircraft "sandwich" encounter. We then ran Monte Carlo simulations with and without the change using the newly developed United States correlated airspace encounter model. We then compared the outcome of each encounter with and without the change.

We simulated 500,000 encounters where the first aircraft was equipped with TCAS version 7.1 either with or without the proposed change. For the first aircraft, we always used the standard pilot response model. Table 1 shows the various equipage combinations for the second aircraft. We ran the entire set of 500,000 encounters 14 times: 2 (with and without the change) times 7 (intruder and Mode S address combinations).

TABLE C-1

Green-arc-on-weakening simulation results.

Intruder Equipage	Response Model	Higher Mode S Address
Unequipped	n/a	n/a
TCAS Version 7.1	Standard	Aircraft 1
		Aircraft 2
	None	Aircraft 1
		Aircraft 2
TCAS Version 7.1	Standard	Aircraft 1
		Aircraft 2

For each simulated encounter we calculated horizontal miss distance, vertical miss distance, time of closest approach, altitude at closest approach, and the probability of a near mid-air collision and afterward we compared all the values with and without the proposed change. Out of all our simulated encounters, we did not observe a single different outcome when including the aforementioned change. Thus, with a fairly high level of confidence we can be certain that the proposed change does not change the behavior of TCAS in single intruder encounters in CASSATT.

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APPENDIX D
IMPORTANCE SAMPLING

Because the focus of this safety evaluation is on the ability of TCAS to prevent NMACs from occurring, we sample encounters involving NMACs more frequently than encounters that do not result in NMACs. We do this by creating sampling functions for horizontal miss distance, $f(hmd)$, and vertical miss distance, $g(vmd)$. We then draw samples for hmd and vmd from the sampling functions, and assign each sample a weight that is defined by the relative probability density functions of the sampling distribution, $f(hmd)g(vmd)$, and the modeled distribution.

A detailed discussion of how to use importance sampling with the correlated model is described in the correlated model document [7]. Any sampling density that is nonzero over the positive real domain can work for generating hmd and vmd. Ideally, $f(hmd)g(vmd)$ approximates $P(\text{nmac} \mid hmd, vmd, \text{enc})$ in order to reduce the variance of the estimate [14].

In this study, we defined $f(hmd)$ and $g(vmd)$ as step functions over the domain $\{0 \ldots 3\}$ and $\{0 \ldots 6000\}$ respectively. In our model, those domains cover the entire space of possible values for hmd and vmd as required for valid importance sampling. Choosing to use step functions allowed for good control over the shape of the final distribution. In order to choose the step functions for hmd and vmd, we created one million encounters sampled directly from the model, and conducted a limited safety investigation where AC1 was equipped with V7.0 and AC2 was unequipped. From that investigation, we observed the distribution of hmd and vmd for encounters that resulted in an NMAC when one aircraft was equipped with TCAS. When we conducted the investigation, we found that the vast majority of encounters that resulted in an NMAC tended to already have low scripted hmd and vmd. This is reflected in our chosen sampling distributions.

In this study, the sampling procedure we used for hmd was:

$$hmd \sim \left\{ \begin{array}{ll} \text{U}(0, 0.08229) & \text{if } X < 0.95 \\ \text{U}(0.08229, 3) & \text{otherwise} \end{array} \right\}$$

where $\text{U}(a, b)$ represents the uniform distribution between a and b, and $X \sim U(0, 1)$. The sampling procedure we used for vmd was:

$$vmd \sim \left\{ \begin{array}{ll} \text{U}(0, 100) & \text{if } X < 0.475 \\ \text{U}(100, 200) & \text{if } 0.475 \leq X < 0.65 \\ \text{U}(200, 300) & \text{if } 0.650 \leq X < 0.806 \\ \text{U}(300, 300) & \text{if } 0.806 \leq X < 0.892 \\ \text{U}(400, 300) & \text{if } 0.892 \leq X < 0.936 \\ \text{U}(500, 300) & \text{if } 0.936 \leq X < 0.961 \\ \text{U}(600, 300) & \text{if } 0.961 \leq X < 0.974 \\ \text{U}(700, 300) & \text{if } 0.974 \leq X < 0.993 \\ \text{U}(800, 300) & \text{if } 0.993 \leq X < 0.999 \\ \text{U}(900, 6000) & \text{if } 0.999 \leq X < 1 \end{array} \right\}$$

Histograms for the resulting samples are shown in Figure D-1. The figure shows that samples drawn using importance sampling are highly concentrated at low *hmd* and *vmd*.

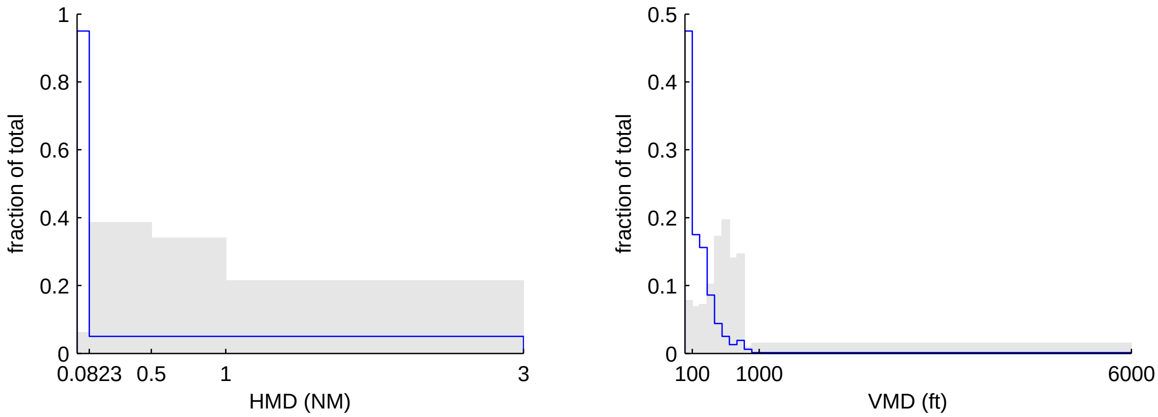

Figure D-1. Histograms of hmd (left) and vmd (right). The sampling distribution is outlined in blue, the observed distribution is shaded.

Figure D-2 shows the convergence curves for $P(\text{nmac} \mid \text{enc})$ for one million direct samples and 500,000 samples drawn using importance sampling from the correlated encounter model. Both approaches produce a steady state estimate of $P(\text{nmac} \mid \text{enc})$ of 0.0030. However, importance sampling reaches steady state with only a fraction of the number of samples required by direct sampling methods. The primary benefit of importance sampling, however, is that many more encounters that test the TCAS logic are generated; thus, we can be confident that we have tested all (or most of) the logic, while still maintaining the proper joint probability distribution to estimate the overall performance accurately. An additional benefit of importance sampling is that by producing a much greater number of difficult encounters, there is a much greater probability that the TCAS logic is exposed to a high number of cases that may produce undesirable results. By further investigating the encounters TCAS failed to resolve in this study, it may be possible to preemptively identify a set of similar problem cases, such as SA01, before a future disaster occurs.

The observed $P(\text{nmac} \mid \text{enc})$, around 0.0026, is slightly lower than what the model predicts. A slight overestimate of $P(\text{nmac} \mid \text{enc})$ in our samples is expected given the way we initialize encounters for simulation. As explained in the documentation for the correlated model, AC1 is temporarily initialized such that it is located at the origin and flying due North at TCA ($x_{1,tca} = 0$, $y_{1,tca} = 0$ and $\psi_{1,tca} = 0$). The correct horizontal location of AC2 relative to AC1 at TCA ($x_{2,tca}$, $y_{2,tca}$) depends on the variables *hmd*, β, and χ from the initial Bayesian network, in addition to the velocity and heading of the two aircraft at TCA. The initialization of the encounter in this manner ensures that the relative positions of the aircraft in the horizontal plane at TCA, defined at 40 s from the beginning of the encounter, matches the parameter values sampled from the model. However, because we do not explicitly model *hmd* and *vmd* at every point during the encounter, in a small number of cases, maneuvering by either aircraft prior to TCA may cause *hmd* and/or *vmd* to be smaller at some point before or after 40 s into the encounter. In an even smaller number of

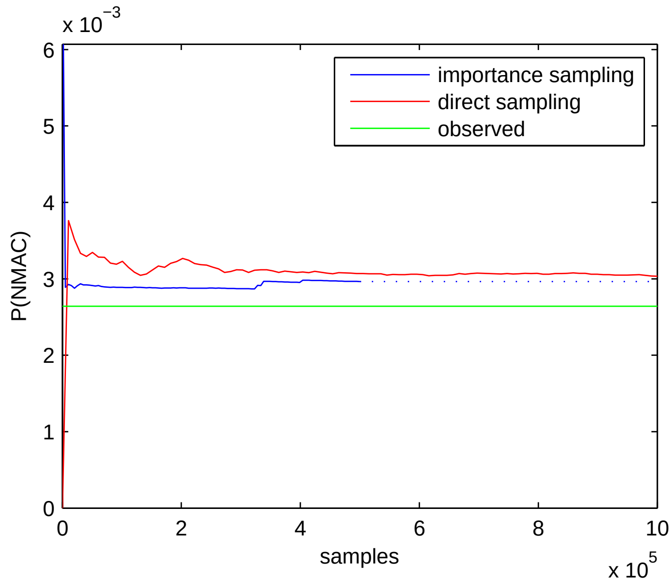

Figure D-2. Convergence curves for importance and direct sampling. Also shown is observed P(NMAC).

cases, those reduced *hmd* and *vmd* values are enough to produce an NMAC. Thus, $P(\text{nmac} \mid \text{enc})$ for our scripted encounters is always slightly greater than the $P(\text{nmac} \mid \text{enc})$ that is modeled. This difference is not meaningful in terms of the validity of our results in terms of risk ratio.

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