Project Report
ATC-359

TCAS Multiple Threat Encounter Analysis

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16. Abstract

The recent development of high-fidelity U.S. airspace encounter models at Lincoln Laboratory has motivated a simulation study of the Traffic Alert and Collision Avoidance System (TCAS) multiple threat logic. We observed from archived radar data that while rarer than single-threat encounters, multiple threat encounters occur more frequently than originally expected. The multi-threat logic has not been analyzed in the past using encounter models.

To generate multi-threat encounters, this report extends the statistical techniques used to develop pairwise correlated encounters. We generated and simulated a large number of multi-threat encounters using the TCAS logic implemented in Lincoln Laboratory's Collision Avoidance System Safety Assessment Tool.

Near mid-air collision (NMAC) count indicates how often close encounters are resolved, unresolved, or induced by TCAS. Change in vertical miss distance shows the effect of the additional threat on the vertical separation between the first two aircraft. Risk ratio measures how the probability of an NMAC changes when an aircraft is equipped with TCAS versus being unequipped.

Study results indicate that in multi-threat encounters, the TCAS logic results in a more than twofold increase in unresolved NMACs and approximately five times more induced NMACs than one-on-one encounters. TCAS provides a safety benefit in multi-threat encounters by issuing resolution advisories that result in increased vertical separation between the equipped aircraft and the first intruder.

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EXECUTIVE SUMMARY

The recent development of high-fidelity U.S. airspace encounter models at Lincoln Laboratory has motivated several follow-on efforts, one of which is a simulation study of the Traffic Alert and Collision Avoidance System (TCAS) multiple threat logic. Radar data from a collection of sensors throughout the U.S. were transferred to Lincoln Laboratory for the purpose of developing the encounter models. From these data, we observed that while rarer than single-threat encounters, multiple threat encounters occur more frequently than originally expected. The multi-threat logic has not been analyzed using an encounter model, and is not as well understood as the single-threat safety logic.

To generate multi-threat encounters, this report extends the statistical techniques used to develop pairwise correlated encounters. We first use the correlated model to generate a one-on-one encounter, then use a modified version of the model to add an additional threat to the encounter. Using this technique, the geometry of the multi-threat encounter is representative of what actually occurs in the airspace. We generated and simulated a large number of multi-threat encounters using the TCAS logic implemented in Lincoln Laboratory's Collision Avoidance System Safety Assessment Tool (CASSATT). In our encounter scenarios, we equipped only one aircraft with TCAS, and the two intruder aircraft with Mode S transponders, since this is most representative of the observed multi-threat encounters.

We use three metrics to analyze the performance of the TCAS multi-threat logic. The first metric, near mid-air collision (NMAC) count, indicates how often NMACs are resolved, unresolved or induced by TCAS in the encounters. Resolved NMACs are those that occur without TCAS but not with TCAS, unresolved NMACs occur both with and without TCAS, and induced NMACs occur with TCAS but not without. The second metric, change in vertical miss distance (VMD), shows the effect of the additional threat on the vertical separation between the first two aircraft in the encounter. The third metric, risk ratio, measures how the probability of an NMAC changes when an aircraft is equipped with TCAS versus being unequipped in the encounters. Risk ratio is used to compare the performance of TCAS in the multi-threat encounters with how it would perform if it could resolve each threat independently. In addition, it allows us to compare its performance only responding to one threat, or essentially disabling the multi-threat logic.

In summary, results from this study show that:

- In multi-threat encounters, the TCAS logic results in a more than twofold increase in the number of unresolved NMACs and approximately five times more induced NMACs than one-on-one encounters. This result is expected because in a multi-threat encounter, an NMAC can occur between the TCAS-equipped aircraft and two intruder aircraft as opposed to just one.

- When the additional threat is added, VMD between the first two aircraft increases in 42% of the encounters, decreases in 29%, and does not change in 29%. This result indicates that TCAS generally provides a safety benefit in multi-threat encounters by issuing resolution advisories (RAs) that result in increased vertical separation at closest point of approach (CPA) between the equipped aircraft and the first intruder.
- Risk ratio is higher with the TCAS Version 7.0 multi-threat logic resolving the situation (13.33%) than if the system could independently resolve each threat (2.72%), but lower than if the multi-threat logic were not implemented at all (71.77%).
- Risk ratio with TCAS Version 7.1 is 13.27%, indicating an improvement over Version 7.0. This improvement is due to changes in the logic that cause resolution advisory (RA) reversals to occur where they previously did not, as well as the change from adjust vertical speed, adjust (AVSA) to level off, level off (LOLO) RAs.

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1. INTRODUCTION

Due to increasing demand for air travel, the traffic density of U.S. airspace is expected to increase significantly in the future. This increased airspace usage will likely lead to a higher number of multi-threat encounters between aircraft equipped with the Traffic Alert and Collision Avoidance System (TCAS) and both equipped and unequipped intruders. The analysis of recent radar data shows a higher occurrence of multi-threat encounters than expected. The safety analysis methods originally used to support the development of TCAS involved simulating a large number of encounters between two aircraft and analyzing the performance of the TCAS logic in resolving these encounters. However, the performance of the TCAS multi-threat logic has not been as rigorously tested using these methods, and the inner workings of the logic are not as well understood. Observing how the logic behaves in simulated encounters leads to a better understanding of how it will perform in real-world situations.

The function of an encounter model is to generate random encounter situations between 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 [1–6]. Lincoln Laboratory recently completed development of a correlated airspace 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. We can then assess the efficacy of the system in reducing the probability of an near mid-air collision (NMAC). Drawing upon the methods used to develop the correlated model, we extend its use to generating encounters between three aircraft that are representative of the types of multi-threat encounters that occur in the airspace. We then simulate a large number of multi-threat encounters using the actual TCAS logic implemented within the Collision Avoidance System Safety Assessment Tool (CASSATT), a fast-time simulation tool also developed at Lincoln Laboratory. This allows us to statistically analyze how the TCAS logic performs in multi-threat encounter scenarios. In addition, we compare the performance of TCAS II Version 7.1 with that of Version 7.0 to observe whether changes to the logic have any effects on multi-threat encounters.

TCAS resolves multi-threat encounters by selecting a resolution advisory (RA) that provides adequate vertical separation from each threat [8]. It may do this by issuing the same RA as it would for a single-threat encounter, or a combination of upward and downward sense RAs (e.g., Do Not Climb and Do Not Descend). The primary concern for multi-threat encounters is that TCAS may issue an improper maneuver that resolves the encounter with the first threat but induces a collision with a secondary threat, or that is incompatible (e.g., simultaneous Climb and Descend RAs).

The term “multi-threat” is used throughout this report to identify encounters between one TCAS-equipped aircraft and more than one intruder aircraft. The multi-threat logic has been referred to in the past as multiaircraft. The term “intruder” can be substituted for threat, although threat is used in the report for consistency.

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2. METHODOLOGY

This section discusses the data gathering, simulation, and performance metrics used to analyze the efficacy of the TCAS logic in resolving multi-threat encounters.

2.1 DATA

The radar data used to build the multi-threat encounter model comes from the 84th Radar Evaluation Squadron (RADES) at Hill AFB, Utah. RADES receives radar data from FAA and Department of Defense sites throughout the United States. They maintain continuous real-time feeds from a network of sensors, including long-range ARSR-4 radars around the perimeter of the United States and short-range ASR-8, ASR-9, and ASR-11 radars in the interior. Radar ranges vary from 60 to 250 NM.

We define an encounter as a situation where two aircraft have lost standard separation and whose trajectories, if extrapolated into the future without pilot intervention, result in a significant chance of collision. We identify multi-threat encounters by determining if any one-on-one encounters share a common aircraft track, and if the time of closest approach (TCA) of the encounters with the common track occur within 10 seconds of each other. Using this procedure, we identified 3803 such multi-threat encounters, with locations shown in Figure 1.

For analysis purposes, we focus on encounters with only three aircraft, representing over 95% of the multi-threat encounters as shown by Figure 2.

In a multi-threat encounter, we define the three aircraft in the encounter as Aircraft 1, Aircraft 2 and Aircraft 3. Aircraft 1 is defined to be the aircraft that is common to both encounters in our database; in other words, Aircraft 1 is involved in an encounter with both Aircraft 2 and Aircraft 3. In many cases, Aircraft 2 is also involved in an encounter with Aircraft 3, but that is not a requirement in our dataset. To differentiate between Aircraft 2 and Aircraft 3, we define Aircraft 2 as the aircraft that has the closest approach to Aircraft 1 in terms of HMD. A similar approach was used in previous studies [9]. In this way, we can think of a multi-threat encounter as two overlapping encounters: an encounter between Aircraft 1 and Aircraft 2 at the same time as an encounter between Aircraft 1 and Aircraft 3.

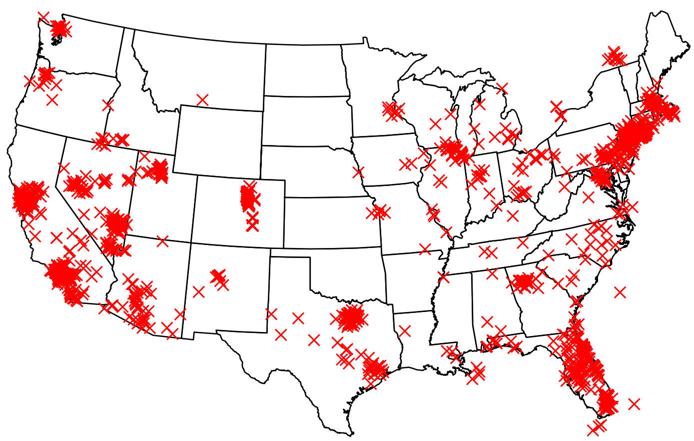


Figure 1. Geographic location of multi-threat encounters in the United States. Each "X" represents one multi-threat encounter.

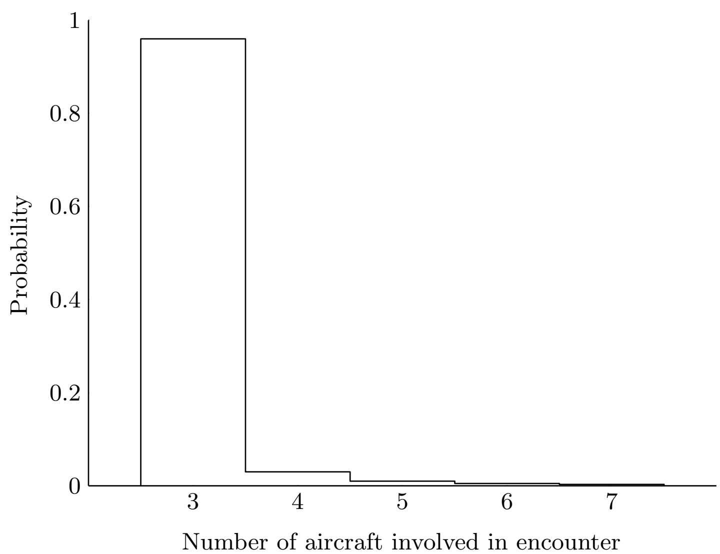


Figure 2. Distribution over the number of aircraft involved in a multi-threat encounter. Over 95% involve three aircraft, but one involved seven aircraft.

2.2 SIMULATION

We use Lincoln Laboratory's CASSATT to evaluate TCAS multi-threat encounters. CASSATT performs fast-time Monte Carlo analysis, taking either real radar tracks or encounter model data as an input and simulating 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 an aircraft dynamic model, TCAS, and a pilot response model.

Aircraft Aircraft dynamics are represented using a tunable 4 degree-of-freedom (DOF) or 6 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 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-threat 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.

CASSATT has been used for prior TCAS safety analyses. 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 [10, 11]. Lincoln Laboratory has also used CASSATT to assess TCAS performance on the U.S. Air Force's Global Hawk unmanned aircraft [12, 13].

With three aircraft involved in an encounter, there are six permutations of altitude at TCA between Aircraft 1 and Aircraft 2. In simulation, we test each of these permutations to determine any sensitivity within TCAS to these situations. We also vary the ranks of the Mode S transponder addresses of Aircraft 1, 2 and 3, because the multi-threat logic is dependent upon Mode S ranking.

2.3 PERFORMANCE METRICS

In order to evaluate the TCAS multi-threat logic using encounter modeling and simulation, several performance metrics were defined. These metrics allow us to quantitatively describe how well the multi-threat logic performs in the simulated encounters relative to the performance of the TCAS logic in encounters between two aircraft. We use NMAC count, change in vertical miss distance (VMD), and risk ratio. The remainder of this section describes these metrics.

2.3.1 Near Mid-Air Collisions

Due to the difficulty of estimating the likelihood of collision based on a close encounter between two or more aircraft, research has instead focused on estimating the probability of an NMAC, which is defined as a loss of separation between two aircraft 500 ft horizontally and 100 ft vertically. For the purposes of the multi-threat study, we focus on the count of total NMACs for a large set of simulated encounters. Although the probability of an induced or unresolved NMAC may be easily computed and understood for single-threat encounters, it is more difficult for multi-threat encounters because there may be up to three pairwise NMACs in one encounter scenario, each with its own probability. Rather than calculating separate probabilities of an NMAC for a given set of encounters, we use the total NMAC count to quantify the overall performance of the multi-threat logic.

By comparing the number of NMACs for a set of simulated single-threat encounters with that of a multi-threat encounter set, we can observe the effect of the additional threat on the encounter geometry. We do not include the number of NMACs between the second and third aircraft since this number is unrelated to the performance of TCAS onboard the primary aircraft in the simulation.

2.3.2 Change in Vertical Miss Distance

The second metric, change in VMD between Aircraft 1 and 2, gives us an idea of how the multi-threat logic causes the TCAS-equipped aircraft to maneuver. This may be in a way that generally makes the situation more safe or less safe than if there were only two aircraft in the encounter. The multi-threat logic could cause TCAS to issue a Climb RA, for instance, where the one-on-one logic would have issued a Do Not Descend RA. This would increase the VMD between the first and second aircraft in the multi-threat encounter compared to the single-threat encounter.

2.3.3 Risk Ratio

Another important performance metric typically used in collision avoidance system safety studies is risk ratio. Risk ratio is the relative probability of an NMAC for two different configurations, typically with and without TCAS. For the multi-threat analysis, the desire is to compare the performance of the multi-threat logic relative to TCAS being able to resolve each threat independently, and relative to avoiding only one of the two threats as it would if the multi-threat logic did not exist. Although independent threat resolution is not physically realistic, it enables us to compare the multi-threat logic to a best-case scenario. We expect TCAS to perform worse than it would in this optimal case, but better than only responding to one of the two threats. The goal for this study is to quantify just how much the performance of TCAS is affected due to the multi-threat logic being activated. We do this by calculating and then comparing risk ratios for various configurations.

3. ENCOUNTER MODELING

Encounters in our analysis are based on the correlated U.S. encounter model recently developed at Lincoln Laboratory [7]. An encounter model specifies the initial positions and orientations of two aircraft in the simulation and the nominal dynamic maneuvers that may occur leading up to TCA. The model produces realistic encounter geometries that a collision avoidance system may be expected to resolve.

Aircraft flight is modeled using a Markov process and represented using a dynamic Bayesian network. Aircraft turn rate, airspeed acceleration and vertical rate may change once per second. Given a set of initial conditions and these dynamic variables, the aircraft trajectories in the encounter can be constructed. Representing aircraft trajectories as a Markov process means that the future state of the trajectory is only dependent on the current state. Dynamic Bayesian networks allow the conditional probability distributions in a Markov process to be compactly represented, and are further discussed elsewhere [14–16].

It is not feasible to create a fully specified multi-threat encounter model given the amount of data we currently possess. A fully specified correlated encounter model with three aircraft would require at least 22 variables, whereas the current correlated model has 16. Each additional variable increases the number of potential variable correlations by an exponential amount, and therefore significantly raises the data requirements to support the additional correlation structure. Compounding the problem, multi-threat encounters in the airspace, as already noted, are relatively rare. Whereas we used approximately 400,000 observed encounters to build the correlated encounter model, we only observed 3,803 multi-threat encounters in the same data set. In addition, if we were to use the fully specified approach, adding an additional threat aircraft would require an entirely new model, increasing both the data requirements and scarcity of observations exponentially with each additional aircraft. The combination of the lack of observed encounters, the increased data requirements, and the inflexibility of a fully specified model requires a different approach to multi-threat encounter modeling.

Our approach is to use the correlated encounter model to generate a one-on-one encounter between two aircraft. We then use a modified version of the encounter model to generate a third aircraft involved in the encounter. The modified version of the encounter model will generate a plausible encounter between Aircraft 1 and Aircraft 3 by conditioning on the already sampled parameters for Aircraft 1. Similar modeling approaches have been used in previous studies when scarce data exists from which to build a model derived purely from observed encounters [13]. The remainder of this section describes the modifications made to the encounter model to accurately generate an additional threat within an encounter.

3.1 CORRELATED ENCOUNTERS

Figure 3 shows the structure of the correlated encounter model Bayesian network, which is based on hundreds of thousands of observed encounters between two manned aircraft [7]. The model variables are airspace class (A), altitude layer (L), airspeed (v), airspeed acceleration ($\dot{v}$), turn rate

($\dot{\psi}$), and vertical rate ($\dot{h}$). Additionally, the correlated model includes aircraft category (C_1 and C_2), which specifies whether the aircraft has a discrete or 1200 Mode A transponder code. The correlated model also specifies the relative geometry of the two aircraft at TCA: horizontal miss distance (hmd), vertical miss distance (vmd), relative heading (β), and bearing (χ).

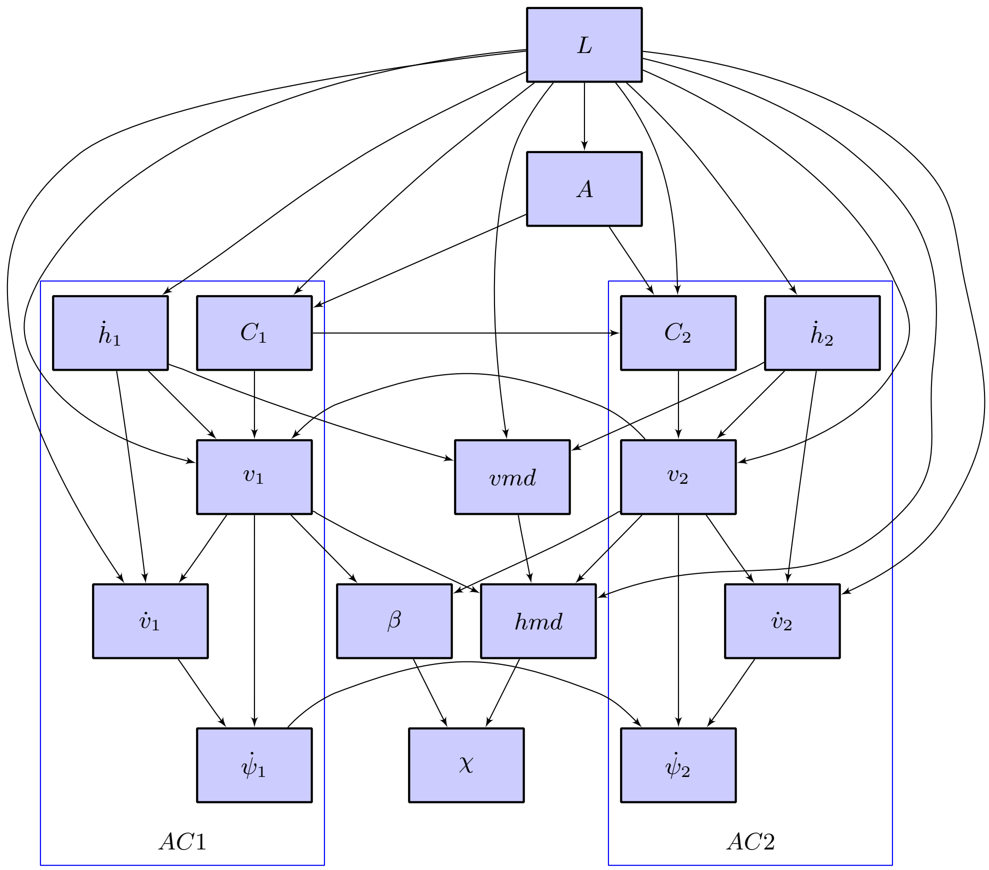


Figure 3. Baseline correlated model. This network represents the initial conditions and relative position at TCA. A separate network is used to specify the time history of the encounter.

3.2 ALTERNATIVE DISTRIBUTIONS

Sampling from the initial Bayesian network in Figure 3 will generate encounters that occur between Aircraft 1 and Aircraft 2. However, we need to ensure that the third aircraft in a multi-threat scenario represents an aircraft likely to be involved in that particular correlated encounter. We want to sample a subset of the encounter variables $\mathcal{A} \subset \mathcal{X}$ from a distribution $P_{alt}(\mathcal{A})$ that is different from the encounter model distribution $P(\mathcal{X})$. Assume we only wanted to sample from a single value of L; then we could assign a value to L and sample in topological order through the rest of the model. However, we cannot simply assign a value to $\dot{\psi}_2$ because its value indirectly affects the distribution of variables topographically higher in the graphical structure such as v_1 and $\dot{\psi}_1$. We must take care when sampling from alternative distributions so that we maintain the important relationships that are reflected in the correlated encounter model.

There are several techniques for sampling from alternative distributions of a Bayesian network [17–19]. Many are described in the correlated encounter model documentation. We chose to create two new graphical structures for this analysis, shown in Figures 4 and 5. Our approach is to manipulate the graphical structure of the Bayesian network such that the parameters of Aircraft 3 can be completely specified from distributions appropriate to that aircraft. In particular, we want to sample the type (C) of Aircraft 3, as well as variables relating to the motion of Aircraft 3 (v, $\dot{v}$, $\dot{\psi}$, $\dot{h}$), and the relative geometry of Aircraft 3 at TCA with respect to Aircraft 1 (hmd, vmd, β and χ).

The parameters for Aircraft 3 are organized at a lower topological level in the Bayesian network so they can be sampled after the parameters for the encounter between Aircraft 1 and Aircraft 2 have been selected. Both graphical structures allow us to assign variables in $\mathcal{A}$, sample from the remainder of the variables in $P_{alt}(\mathcal{A})$, and maintain the important relationships between variables in the initial Bayesian network. For example in Figure 4, it is permissible to assign values to L, A, C_1, $\dot{h}_1$, v_1, $\dot{v}_1$, $\dot{\psi}_1$, which all belong to $\mathcal{A}$, and then sample the remaining variables that specify Aircraft 2 and the relative geometry of the aircraft at TCA. We would use that graphical model to sample encounters when we want Aircraft 3 to be below Aircraft 1 at TCA, and we would use the graphical model in Figure 5 when we want Aircraft 3 to be above Aircraft 1 at TCA.

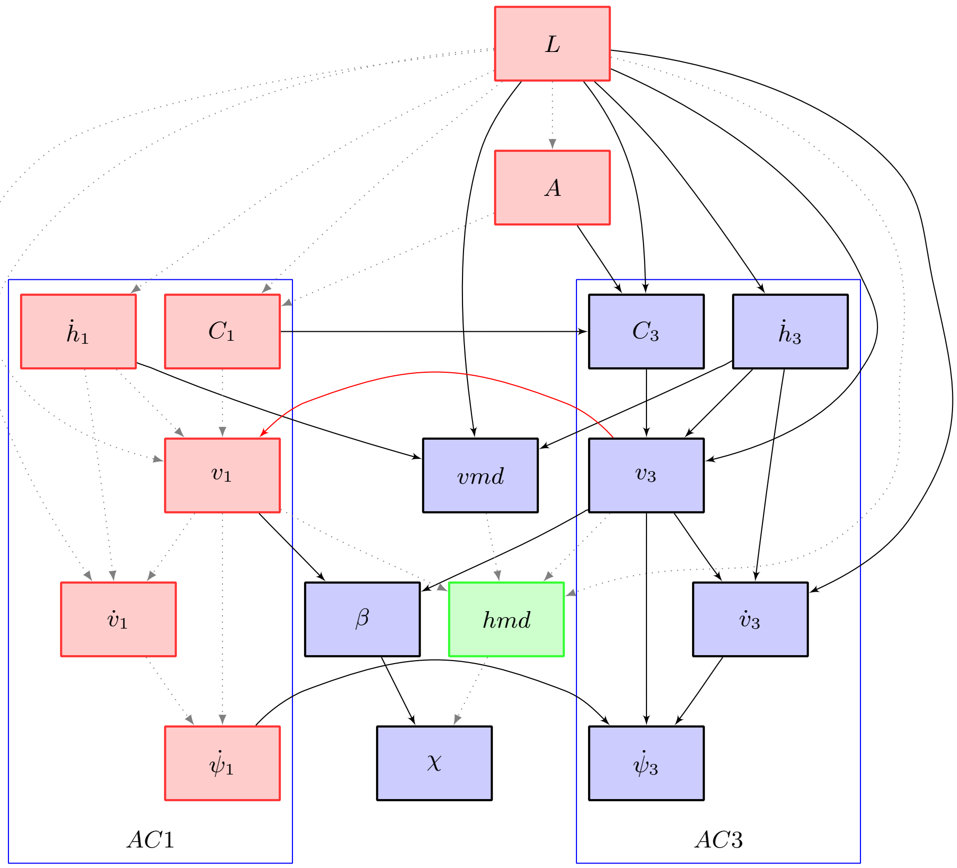


Figure 4. First multi-threat encounter model graphical structure designed to generate Aircraft 3 trajectories that are below Aircraft 1. The red arrows highlight arcs reversed from the original graphical structure. Dotted arrows denote that the original dependency is no longer used to assign variables for the multi-threat encounter. Red nodes indicate that the variable is not sampled, but is rather held fixed. Green nodes indicate that the distribution of the variable is modified to reflect multi-threat encounter characteristics.

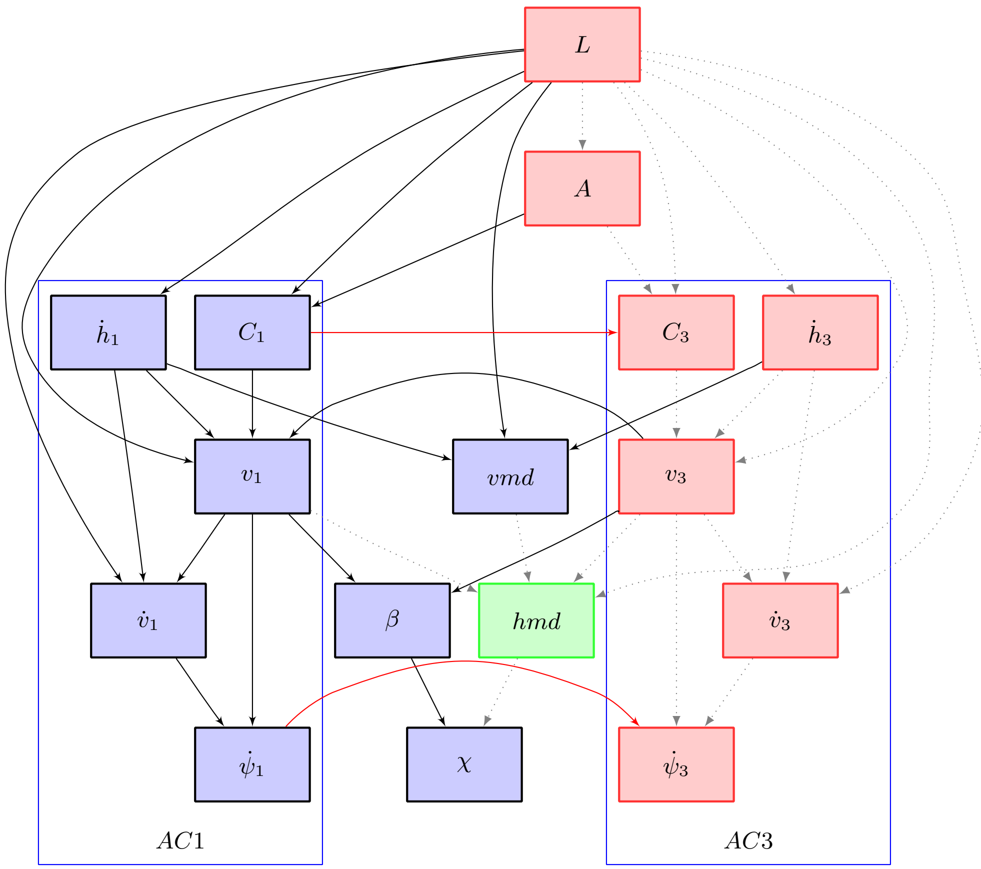


Figure 5. Second multi-threat encounter model graphical structure designed to generate Aircraft 3 trajectories that are above Aircraft 1.

3.3 THIRD AIRCRAFT PROPERTIES

We assign the variables in $\mathcal{A}$ to generate trajectories that are representative of the third aircraft by modifying the distributions of variables highlighted in red from Figures 4 and 5. Analysis of the 3803 observed multi-threat encounters indicate that the encounters between Aircraft 1 and Aircraft 3 have very similar parameter distributions to the encounters between Aircraft 1 and Aircraft 2, except for the distribution of HMD. The HMD distributions for the pairwise encounters are shown in Figure 6.

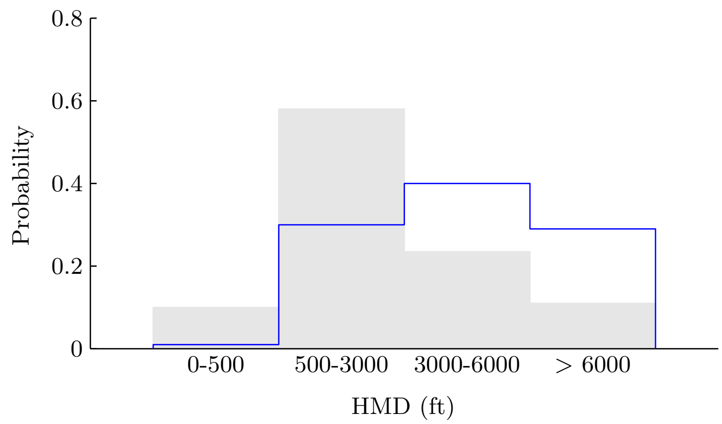


Figure 6. HMD distributions. Solid gray distributions are for Aircraft 1 - Aircraft 2 encounters and the blue line is for Aircraft 1 - Aircraft 3 encounters.

For this study, we assume that the distributions over L and A do not change for multi-threat encounters versus one-on-one encounters, although this assumption may be adjusted in future studies that focus on the overall risk of multi-threat encounters in the national airspace.

4. RESULTS

To evaluate the performance of the TCAS multi-threat logic, we randomly sampled one million encounters from the multi-threat encounter model using the methods described in Section 3.2. The focus of the analysis is on those encounters where the TCAS multi-threat logic was activated in the simulation, which comprised 253,720 of the one million total encounters. As described in Section 2.3, the performance metrics used to evaluate the TCAS multi-threat logic are the number of NMACs, the change in VMD between Aircraft 1 and Aircraft 2, and the risk ratios for several test conditions. This section presents the analysis results based on the selection of these performance metrics.

Table 1 shows the equipage combinations for each aircraft in the simulation. Mode S transponder equipage assumes 25 ft altitude quantization. We equip the primary aircraft (Aircraft 1) with TCAS Version 7.0 with 25 ft altitude quantization and a standard pilot response of 5 s for the initial RA and 2.5 s for any subsequent RAs. Simulating all aircraft equipped with Mode S transponders provides a baseline case for analysis, and simulating Aircraft 1 versus Aircraft 2 and then Aircraft 1 versus Aircraft 3 allows us to compare the TCAS response for multi-threat encounter scenarios with how it would respond to only one of the two threats. Additionally, we simulate a set of multi-threat encounters where Aircraft 1 is equipped with TCAS Version 7.1 and both intruders are equipped with a Mode S transponder. TCAS Version 7.1 reflects two significant changes to the logic known as Change Proposal 112E (CP112E) and Change Proposal 115 (CP115). CP112E improves the logic by triggering reversal RAs at the proper point in an encounter where two aircraft are simultaneously climbing or descending. CP115 resolves ambiguity in some encounters by replacing adjust vertical speed, adjust (AVSA) RAs with level off, level off (LOLO) RAs. The updated logic has been tested at Lincoln Laboratory in pairwise encounters [11]. We simulate TCAS Version 7.1 in this study in order to observe the effect of the logic changes and determine whether any safety concerns exist due to the geometries of multi-threat encounters.

TABLE 1

Aircraft equipage combinations. Columns represent sets of encounters with varying combinations of equipage on each aircraft in the simulation.

Aircraft	Equipage			
1	Mode S	TCAS	TCAS	TCAS
2	Mode S	Mode S	Mode S	
3	Mode S	Mode S		Mode S

4.1 NEAR MID-AIR COLLISION COUNT

Table 2 shows the effect of the additional threat on the number of NMACs resolved, unresolved and induced by TCAS Version 7.0. Simulation results show that the TCAS logic resolves slightly fewer NMACs and causes a higher number of unresolved and induced NMACs when an additional threat is added. This result is expected because of the higher number of close geometries that result when adding an additional threat to a pairwise encounter. For example, a second threat aircraft can cause TCAS to issue an RA where it did not issue one for the first threat, and this may or may not resolve the NMAC that occurred without TCAS.

TABLE 2

Number of NMACs resolved, unresolved, and induced for the single-threat encounter model versus the multi-threat model. Multi-threat logic was activated in 253,720 encounters.

	NMAC Count	
NMAC Type	Single-threat Encounters	Multi-threat Encounters
Resolved	39711	39327
Unresolved	316	700
Induced	203	1055

4.2 CHANGE IN VERTICAL MISS DISTANCE

Figure 7 depicts the VMD between Aircraft 1 and Aircraft 2 for a random sample of single-threat encounters versus the same encounters with an additional threat. The case where VMD between Aircraft 1 and Aircraft 2 increases due to the additional threat is most common, occurring in 42% of the encounters. This results from encounter geometries where the second threat (Aircraft 3) was initially closer to the TCAS-equipped aircraft (Aircraft 1) than the first threat (Aircraft 2). This causes TCAS to issue a more restrictive RA than in the single-threat encounter, resulting in an increase in VMD between Aircraft 1 and Aircraft 2. In encounter geometries where VMD between Aircraft 1 and Aircraft 2 decreases with the additional threat, 29% of the encounters, TCAS attempts to resolve encounters with the second threat after already issuing an RA in response to the first threat. This leads to the TCAS-equipped aircraft maneuvering in such a way that the vertical separation from the original threat is smaller. In 29% of the encounters, VMD does not change due to the second threat. The geometry of these encounters is such that the initial vertical separation between the TCAS-equipped aircraft and the second threat is greater than with the first threat. Although the TCAS multi-threat logic tracks the second threat, it issues the same RA as it does in the single-threat encounter.

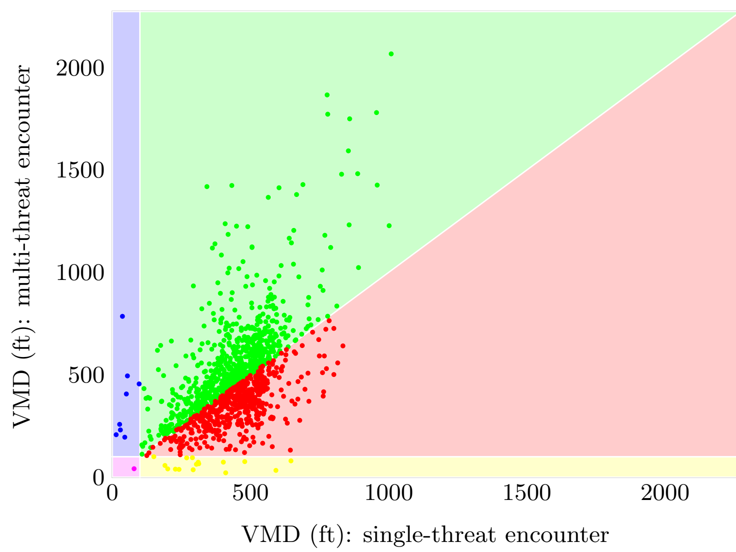


Figure 7. Vertical miss distance between Aircraft 1 and Aircraft 2 for single-threat encounters vs. multi-threat encounters. Approximately 4,000 samples are shown where VMD for single-threat encounters is different from that of multi-threat encounters, but the pattern is reflective of complete encounter set. VMD is defined at the point of minimum horizontal separation between Aircraft 1 and Aircraft 2.

4.3 RISK RATIO

In order to evaluate the performance of the TCAS multi-threat logic, we calculated risk ratios for three cases:

- **Case 1**: Multi-threat encounters with the TCAS multi-threat logic on Aircraft 1 attempting to resolve any NMACs that may occur with the primary threat (Aircraft 2) or the additional threat (Aircraft 3).
- **Case 2**: Encounters where TCAS is able to resolve each threat independently. This provides a best-case, though physically unrealistic, comparison for performance analysis of the multi-threat logic.
- **Case 3**: Encounters where TCAS responds to only one of the two threats in the encounter with equal likelihood (essentially turning the multi-threat logic off and allowing a worst-case comparison).

The risk ratio calculation only takes into account those encounters where the TCAS multi-threat logic is activated, 253,720 of the total one million encounters. Figure 8 shows the risk ratios for each of these three cases. Case 2 results in the lowest risk ratio, roughly one-fifth that of the multi-threat encounter results. With the multi-threat logic activated, however, TCAS performs approximately five times better than it would if the multi-threat logic did not exist.

The risk ratio for TCAS Version 7.1 is 13.27%, whereas for Version 7.0 it is 13.33%. This indicates a slight improvement in multi-threat encounters with the updated logic. The types of multi-threat geometries where TCAS Version 7.1 provides an improvement are often those where the TCAS-equipped aircraft (Aircraft 1) is climbing and "sandwiched" between one threat above and one below. TCAS Version 7.0 may issue an AVSA RA to reduce the climb rate of Aircraft 1, and the multi-threat logic would not be activated because the second threat is far enough below Aircraft 1 not to pose a threat. However, with TCAS Version 7.1 the AVSA RA becomes a LOLO RA, and TCAS then begins to track the second threat. The multi-threat logic is activated and issues a Do Not Climb/Do Not Descend RA, and the vertical separation increases with both threats. We also observed several encounters in simulation in which TCAS Version 7.1 issues a reversal where Version 7.0 does not. Version 7.1 provides a safety benefit in these encounters as well.

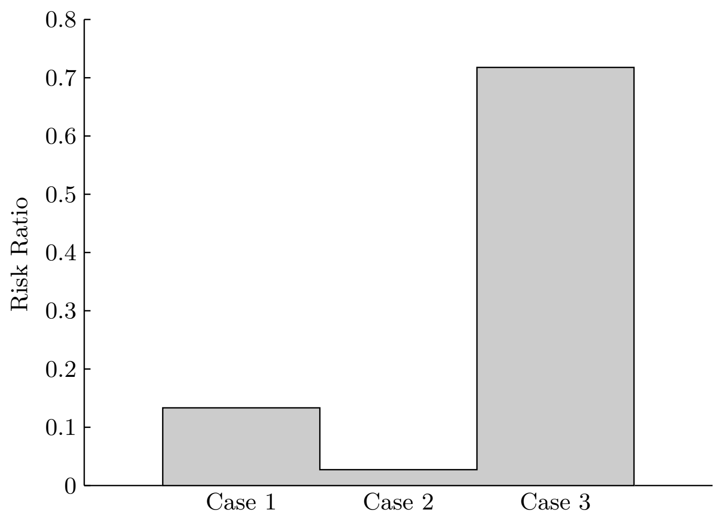
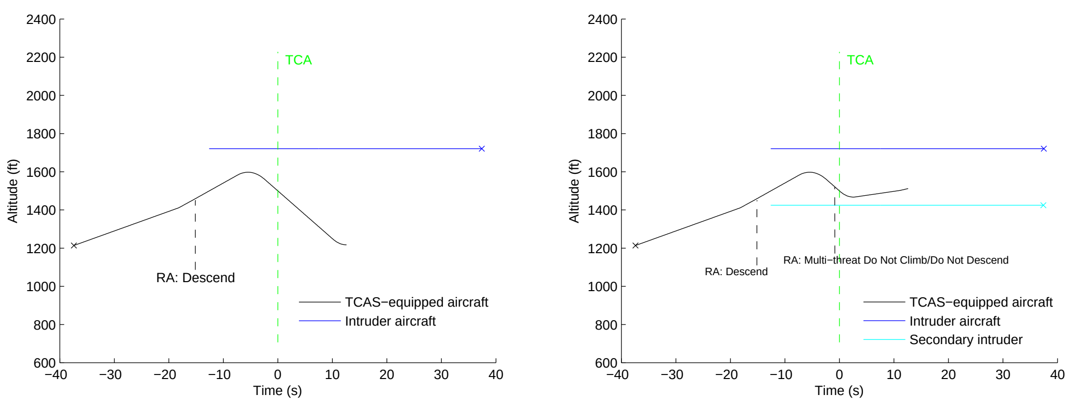


Figure 8. Risk ratio for full encounter set. Case 1: Multi-threat encounters; Case 2: Independently resolved encounters; Case 3: Multi-threat logic off.

4.4 EXAMPLE ENCOUNTER

Figure 9 shows vertical profile trajectories for an example single-threat encounter compared to the same encounter with an additional threat. The vertical axis represents aircraft altitude, and the horizontal axis shows time for each aircraft as it nears closest point of approach (CPA), denoted by a dashed line at zero seconds. For the single-threat encounter, TCAS issues a "descend" RA and the equipped aircraft responds to the RA resulting in a safe vertical separation at CPA. In the multi-threat encounter, however, TCAS issues a descend RA followed by a Do Not Climb/Do Not Descend RA after the additional threat is detected and tracked. This occurs in order to keep the TCAS-equipped aircraft between the two threat aircraft vertically. The VMD between Aircraft 1 and Aircraft 2 is decreased to less than it was in the single-threat encounter. In addition, although TCAS resolves the NMAC between Aircraft 1 and Aircraft 2, an NMAC is induced between Aircraft 1 and Aircraft 3. Although it is rare in the simulation results for TCAS to induce a secondary NMAC, the case of VMD decreasing between the first two aircraft due to the presence of an additional threat is much more common as discussed in Section 4.2. This encounter, while simulated, is a realistic example of what can happen when the TCAS multi-threat logic is activated. If TCAS had tracked the additional threat earlier in the encounter, it may have issued the Do Not Climb/Do Not Descend RA in time to resolve both NMACs.



(a) Single-threat encounter.

(b) Multi-threat encounter.

Figure 9. Example simulated single-threat encounter compared to same encounter with additional threat. Aircraft 1 equipped with TCAS, Aircraft 2 and Aircraft 3 equipped with Mode S transponders.

4.5 SUMMARY

In general, the TCAS multi-threat logic performs well in encounters where it is activated. Our simulated encounters reflect complex situations that occur in the airspace when TCAS must issue RAs in response to more than one threat. Simulation also allows us to test TCAS performance in encounter geometries that may be quite rare in reality, but nonetheless are challenging for TCAS to handle. Although the logic can induce NMACs with a secondary threat, we found very few geometries in which the multi-threat logic issued RAs that induced NMACs with both threats.

We also found that the multi-threat logic did not issue any incompatible RAs in the simulation. In 42% of the encounters, the logic caused the situation to be improved between the equipped aircraft and the first threat due to responding to the second threat.

The multi-threat logic provides a significant safety benefit compared to the absence of the logic. If TCAS could only track and respond to one threat aircraft at a time, notably more NMACs would be induced with the presence of a secondary threat.

We found that TCAS Version 7.1 in multi-threat encounters provides a 0.45% increase in safety compared to Version 7.0. The changes in the logic that are reflected in Version 7.1 work in conjunction with the multi-threat logic to resolve encounter geometries like those described in Section 4.4.

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5. CONCLUSION

This document presented results from an analysis of the TCAS multi-threat logic using a Monte Carlo simulation of multi-threat encounters derived from the correlated U.S. airspace encounter model.

An encounter model for more than two aircraft could not be constructed with high enough fidelity based on the amount of data available. For this reason, we extended the correlated encounter model so that the parameters of the third aircraft in the encounters were representative of realistic geometries in the airspace. We then generated and simulated multi-threat encounters using equipage combinations of a transponder or TCAS on the primary aircraft, and a transponder on both intruder aircraft.

The results of this analysis showed that encounters where the TCAS multi-threat logic was activated resulted in a higher number of unresolved and induced NMACs than one-on-one encounters. This result indicates that TCAS does have the potential to induce NMACs with secondary threats due to the equipped aircraft's response to primary threat aircraft. In addition, the VMD between the original two aircraft in the encounters was more likely to increase than to decrease with the addition of another threat aircraft. This indicates that TCAS provides a safety benefit by commanding more conservative avoidance maneuvers when more than one threat aircraft are tracked by the system. Finally, the risk ratio for encounters where the multi-threat logic is activated was higher than if TCAS could respond to each threat independently, but lower than if the multi-threat logic did not exist and TCAS could only respond to one threat.

Several additional conditions could be tested in the future, such as pilot RA response times, altimeter quantization, and equipping a second aircraft with TCAS in the simulation. Near-term future work could also include a more focused analysis of particular multi-threat encounter geometries where TCAS has trouble resolving the situation. Simulation and visualization tools facilitate understanding of the effects of the TCAS multi-threat logic in ways that are not possible using physical testing. There were a number of encounters in this analysis where TCAS resolved an NMAC with the primary threat but induced an NMAC with a secondary threat. Although these were rare, it would be of interest to examine the geometries more closely. For example, the initial climb rates and altitudes of each aircraft and the scripted, or planned, maneuvers throughout the encounter may significantly impact the ability of TCAS to resolve the encounter. Additionally, encounters where TCAS induced NMACs with both threats could be examined in order to determine if there are geometry conditions such as slow closure rates that prove difficult for TCAS to handle.

The actual risk of multi-threat encounters in U.S. airspace is not known precisely, but it is lower than that of single-threat encounters. Because of this, a future collision between one or more TCAS-equipped aircraft is not likely to be induced due to an additional threat. As soon as enough data exists, the likelihood of a multi-threat induced collision may be estimated to the same degree of confidence as a collision between two aircraft. In the meantime, research effort can be put into additional testing and understanding of the multi-threat logic.

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REFERENCES

[1] MITRE, "System safety study of minimum TCAS II," MITRE, Technical Rep. MTR-83W241 (1983).

[2] M.P. McLaughlin, "Safety study of the Traffic Alert and Collision Avoidance System (TCAS II)," MITRE Corporation, Technical Rep. MTR 97W32 (1997).

[3] T.A. Choyce and K.M. Ciaramella, "Test and evaluation of TCAS II logic version 7," Federal Aviation Administration (2000).

[4] ICAO, "Surveillance, radar and collision avoidance," in *ICAO Standards and Recommended Practices*, vol. IV, annex 10 (1998).

[5] T. Miquel and K. Rigotti, "European encounter model," CENA/Sofréavia and QinetiQ, Technical Rep. ACASA/WP1/186/D (2002).

[6] S. Chabert, "Safety encounter model focused on issue SA01a," CENA/Sofréavia and QinetiQ, Technical Rep. SIRE/WP2/21/D (2005).

[7] M.J. Kochenderfer, L.P. Espindle, J.K. Kuchar, and J.D. Griffith, "Correlated encounter model for cooperative aircraft in the national airspace system version 1.0," MIT Lincoln Laboratory, Project Report ATC-344 (2008).

[8] FAA, "Introduction to TCAS II Version 7" (2000).

[9] T. Arino, K. Carpenter, S. Chabert, H. Hutchinson, T. Miquel, B. Raynaud, K. Rigotti, and E. Vallauri, "Studies on the safety of ACAS II in Europe," Eurocontrol, Technical Rep. ACASA/WP-1.8/210D (2002).

[10] RTCA, "Safety analysis of proposed change to TCAS RA reversal logic," RTCA, Technical Rep. RTCA/DO-298 (2005).

[11] Espindle, Griffith, and Kuchar, "Safety analysis of upgrading to TCAS Version 7.1 using the 2008 correlated encounter model," MIT Lincoln Laboratory, Project Report ATC-349 (2009).

[12] T.B. Billingsley, *Safety analysis of Traffic Alert and Collision Avoidance System on Global Hawk using airspace encounter models*, Master's thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology (2006).

[13] Griffith and Kuchar, "Evaluation of TCAS on Global Hawk with US airspace encounter models," MIT Lincoln Laboratory, Project Report ATC-353 (2009).

[14] J. Pearl, *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*, San Francisco, CA: Morgan Kaufmann (1988).

[15] F.V. Jensen, *Bayesian Networks and Decision Graphs*, Springer Verlag (2001).

[16] R.E. Neapolitan, *Learning Bayesian Networks*, Upper Saddle River, NJ: Prentice Hall (2004).

[17] H.L. Chin and G.F. Cooper, "Belief network inference using simulation," in *Uncertainty in Artificial Intelligence* (1989), pp. 129–147.

[18] W. Buntine, "Operations for learning with graphical model," *Journal of Artificial Intelligence Research* 2, 159–225 (1994).

[19] R.D. Shachter and M.A. Peot, "Approaches to general probabilistic inference on belief networks," in *Uncertainty in Artificial Intelligence* (1990), pp. 221–231.