# Next-Generation Airborne Collision Avoidance System

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In response to a series of midair collisions involving commercial airliners, Lincoln Laboratory was directed by the Federal Aviation Administration in the 1970s to participate in the development of an onboard collision avoidance system. In its current manifestation, the Traffic Alert and Collision Avoidance System is mandated worldwide on all large aircraft and has significantly improved the safety of air travel, but major changes to the airspace planned over the coming years will require substantial modification to the system. Recently, Lincoln Laboratory has been pioneering the development of a new approach to collision avoidance systems that completely rethinks how such systems are engineered, allowing the system to provide a higher degree of safety without interfering with normal, safe operations.

» **Building a collision avoidance system** that can meet the safety standards required of commercial aviation is challenging. Lincoln Laboratory, in collaboration with other organizations, spent decades developing and refining the system that is in use today [1]. There are several reasons why creating a robust system is difficult. The sensors available to the system are imperfect and noisy, resulting in uncertainty in the current positions and velocities of the aircraft involved. Variability in pilot behavior and aircraft dynamics makes it difficult to predict where the aircraft will be in the future. Also, the system must balance multiple competing objectives, including both safety and operational considerations.

Over the past few years, Lincoln Laboratory has been developing advanced algorithmic techniques for addressing these major challenges for collision avoidance. These techniques rely upon probabilistic models to represent the various sources of uncertainty and upon computer-based optimization to obtain the best possible collision avoidance system. Simulation studies with recorded radar data have confirmed that such an approach leads to a significant improvement to safety and operational performance [2]. The Federal Aviation Administration (FAA) has formed a team of organizations to mature the system, which has become known as Airborne Collision Avoidance System X (ACAS X). A satisfactory proof-of-concept flight test in 2013 will strengthen the goal of making ACAS X the next international standard for collision avoidance.

## History

Because the sky is so big and aircraft so small during the early years of aviation, there were very few midair collisions. By the 1950s, air travel had become commonplace, and the skies became more crowded. In 1956, a midair collision over the Grand Canyon resulted in 128 fatalities. At the time, this was the worst commercial air disaster in history. The collision caused a press frenzy, congressional hearings, and the establishment of the FAA in 1958.

The establishment of the FAA led to major improvements in both airspace design and air traffic control. The airspace was designed to keep aircraft separated. For example, depending on whether aircraft were flying west or east, they were expected to fly at different altitudes. Air traffic controllers relied on ground-based radars, keeping aircraft safely separated by calling out traffic to pilots and vectoring aircraft.

The enhancements to airspace design and air traffic control significantly improved the safety of the airspace. However, there were still midair collisions. A midair collision involving a commercial airliner over San Diego, California, in 1978 resulted in 144 fatalities (see Figure 1), and another commercial airliner collision over Cerritos, California, in 1986 resulted in 82 fatalities. These two collisions, in particular, convinced Congress that an additional layer of collision protection was needed in the form of an onboard system. This system would provide an independent safety net to protect against human error, both by air traffic controllers and pilots, and the failures and limitations of visual see and avoid (factors that contributed to the collisions).

Development of an onboard capability started shortly after the midair collision over the Grand Canyon. Early concepts focused on primary radar surveillance that sends out energy pulses and measures the timing of the echo to infer distance. This approach did not work well for a variety of reasons, including the inability to accurately estimate the altitude of the intruder. The focus shifted to beacon-based systems that made use of the transponders already on board most aircraft. An aircraft would send out an interrogation over the radio link and measure the amount of time required for the aircraft to reply. Information about altitude and intended maneuvers could also be shared across this radio data link. The initial FAA system, called Beacon Collision Avoidance System or BCAS, was designed to operate in low-density airspace. The collision over San Diego spurred the development of TCAS, or the Traffic Alert and Collision Avoidance System. It was based on the fundamental concepts of BCAS, but there were enhancements that enabled its use in high-density airspace. The development spanned several decades as shown in Figure 2, and Lincoln Laboratory was a key leader in the design of both systems. The collision over Cerritos led to Congress mandating the use of TCAS in the United States, and now TCAS is required on all large passenger and cargo aircraft worldwide [3].


Hans Wendt

**FIGURE 1.** The collision between Pacific Southwest Airlines Flight 182, shown here, and a Cessna 172 aircraft resulted in the loss of 144 lives on 25 September 1978.

## Challenges for TCAS

TCAS has been very successful in preventing midair collisions over the years, but the way in which the logic was designed limits its robustness. Fundamental to TCAS design is the use of a deterministic model. However, recorded radar data show that pilots do not always behave as assumed by the logic. Not anticipating the spectrum of responses limits TCAS's robustness, as demonstrated by the collision of two aircraft in 2002 over Überlingen, Germany. TCAS instructed one aircraft to climb, but one pilot descended in accordance with the air traffic controller's instructions (illustrated in Figure 3), leading to a collision with another aircraft whose pilot was following TCAS. If TCAS recognized the noncompliance of one of the aircraft and reversed the advisory of the compliant aircraft from a descend to a climb, the collision would have been prevented. A modification was later developed to address this specific

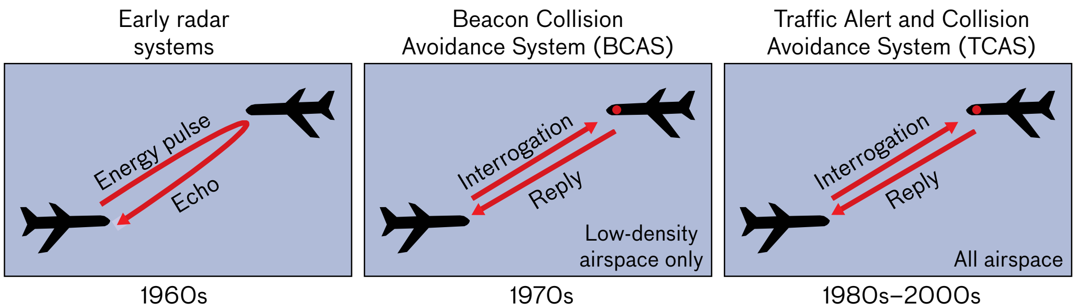



**FIGURE 2.** The development of an onboard collision avoidance system spanned several decades.

situation, but improving the overall robustness of the logic requires a fundamental design change [4].

Just as the airspace has evolved since the 1950s, it will continue to evolve over the next decade. Significant change will occur with the introduction of the next-generation air traffic management system, which will be based on satellite navigation. This improved surveillance will allow aircraft to fly closer together to support traffic growth. Unfortunately, the current version of TCAS cannot support the safety and operational requirements of this new airspace. With aircraft flying closer together, TCAS will alert pilots too frequently to be useful.

To meet these requirements, a major overhaul of the TCAS logic and surveillance system is needed. TCAS is currently limited to large aircraft capable of supporting its hardware and power requirements. The aircraft must also have sufficient performance to achieve the required vertical rates of climb or descent that the advisories currently demand. Although a collision avoidance system for small aircraft might help improve safety within general aviation, TCAS cannot be adapted for small aircraft without a costly redesign.

## ACAS X Program

The ACAS X program will bring major enhancements to both surveillance and the advisory logic. The system will move from the beacon-only surveillance of TCAS to a plug-and-play surveillance architecture that supports surveillance based on global positioning system (GPS) data and that accommodates new sensor modalities, including radar and electro-optical sensors, which are especially important for unmanned platforms. The new surveillance capabilities will also enable collision avoidance protection for new user classes, including small, general-aviation aircraft that are not currently equipped with TCAS [5].

ACAS X represents a major revolution in how the advisory logic is generated and represented. Instead of using ad hoc rule-based pseudocode, ACAS X represents the logic using a numeric table that has been optimized with respect to models of the airspace. This new approach improves robustness, supports new requirements, and reduces unnecessary alerts. The process adopted by ACAS X greatly simplifies development and is anticipated to significantly lower the implementation and maintenance costs [6].

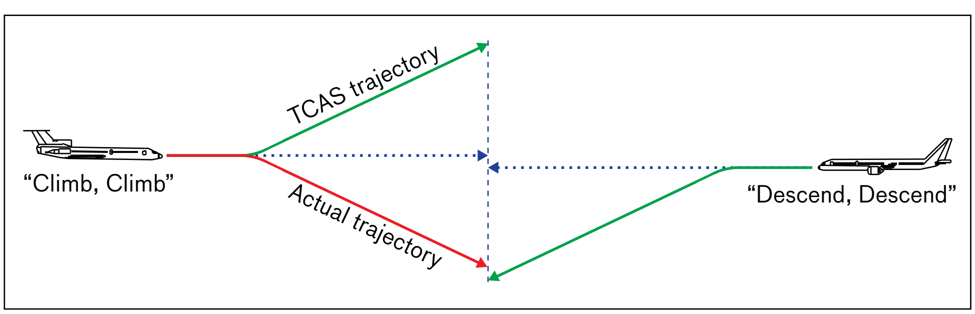
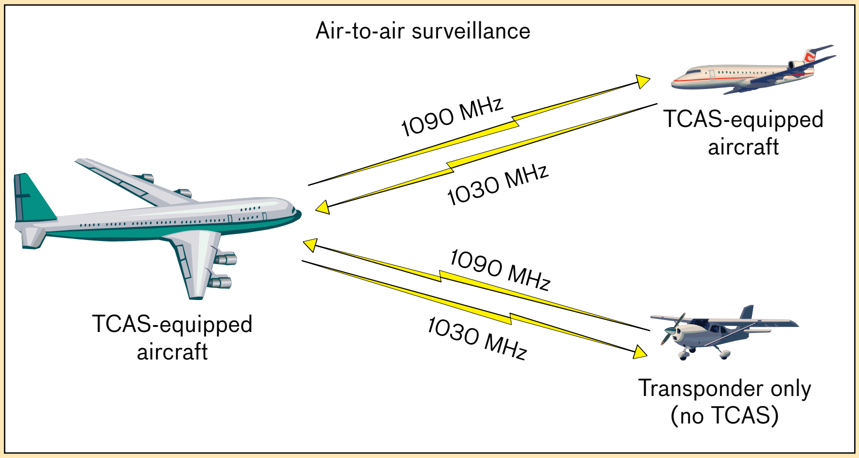



**FIGURE 3.** Two TCAS-equipped aircraft collided over Überlingen on 1 July 2002 due to multiple failures in the air traffic system and associated safety nets. TCAS issued advisories to both aircraft, but one pilot followed conflicting air traffic controller instructions, and the TCAS logic did not allow a necessary reversal.

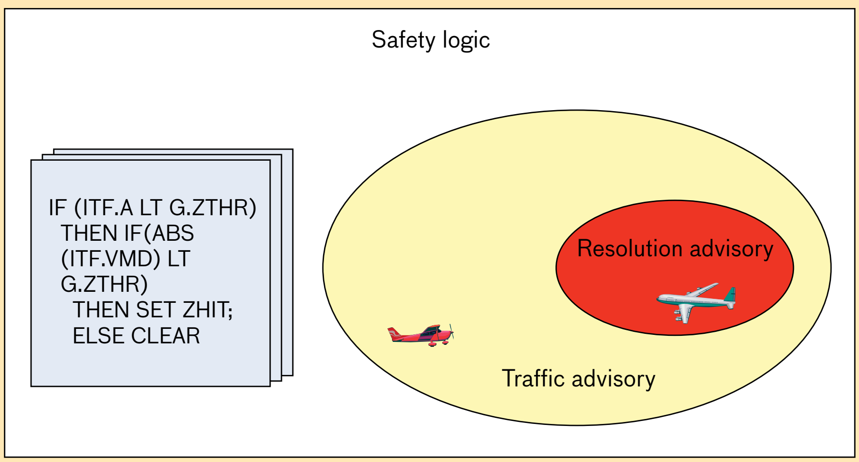
# How TCAS Works

There are four main components of TCAS: airborne surveillance, safety logic, vertical advisories, and a pilot interface. If another airborne aircraft is a potential threat, TCAS issues a traffic advisory (TA), which gives the pilots an audio announcement "Traffic, Traffic" and highlights the intruder on a traffic display. The TA is intended to help pilots achieve visual acquisition of other aircraft and prepare the pilots for a potential avoidance maneuver. If a maneuver becomes necessary, the system will issue a resolution advisory (RA), instructing the pilots to climb or descend to maintain a safe distance. There is an audio announcement of the required vertical maneuver, and the range of acceptable vertical rates is shown on the vertical speed indicator. On some aircraft, additional pitch guidance is provided to pilots.

TCAS may issue a variety of different advisories, including do not climb or descend, limit climb or descend to 500, 1,000, or 2,000 ft/min, level-off, climb or descend at 1,500 ft/min, increase climb or descend to 2,500 ft/min, or maintain current vertical rate. Depending on how the encounter evolves, TCAS may strengthen, weaken, or reverse the direction of the advisory. Note that an RA provides vertical guidance only; TCAS does not issue




**The TCAS surveillance unit interrogates nearby transponder-equipped aircraft. Traffic range, bearing, and altitude estimates are calculated based on the received time, location, and content of the reply. If the tracked aircraft is declared a threat and is also TCAS-equipped, the two TCAS units coordinate complementary advisories through discrete messages.**

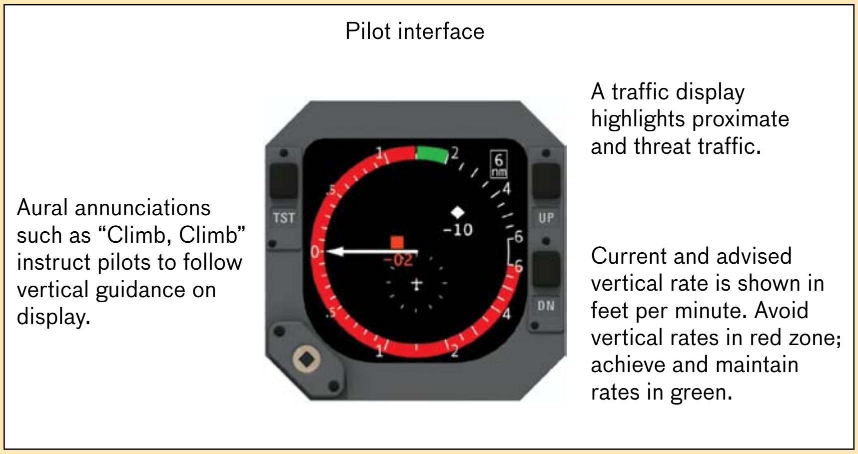



**Advisory logic uses deterministic and heuristic rules to issue alerts against a potential threat on the basis of time of closest approach and projected miss distance.**

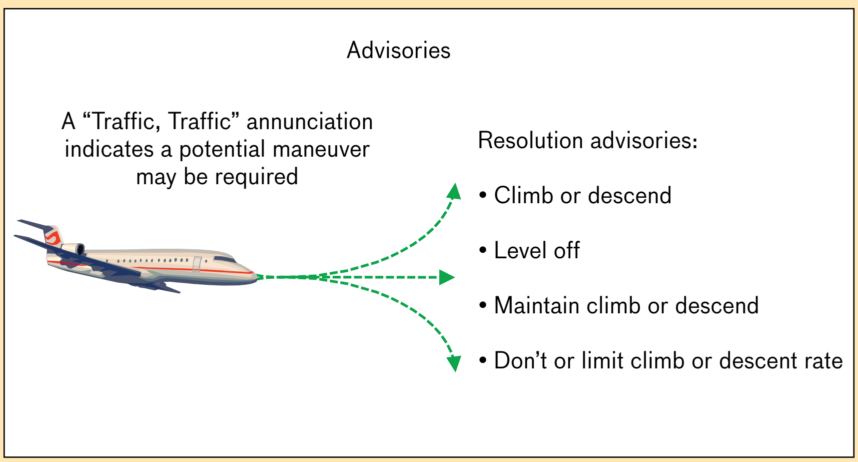
**Logic Optimization**

The logic optimization process takes as input a probabilistic dynamic model and a multi-objective utility model. The probabilistic dynamic model is a statistical representation of where the aircraft will be in the future, and the multi-objective utility model represents the safety and operational objectives of the system. We then use an optimization process called dynamic programming to produce a numeric lookup table [7]. This optimization requires about 10 minutes on a single thread on a modern desktop computer. The resulting table occupies about 300 MB of memory, uncompressed. Although the processing and memory requirements are quite modest according to today's standards, this kind of approach was not feasible when TCAS was originally developed.

A numeric table is a major departure from how




**Pilots have a traffic display showing the relative range, bearing, and altitude of all tracked targets. When an alert is issued, the traffic symbology highlights the intruder, the traffic or resolution advisory is annunciated aurally, and the vertical rate to achieve or avoid is shown on a vertical speed indicator.**




**Traffic alerts are issued to advise pilots that another aircraft is a potential threat and to prepare for a resolution advisory if necessary. A resolution advisory commands specific vertical-only maneuvers that will satisfy safety goals with minimal maneuvering.**

horizontal maneuvers such as heading changes or turns. After the encounter has been resolved, TCAS declares "Clear of Conflict."

The logic for specifying when to alert and what advisory to issue is represented as a large collection of rules. The TCAS logic begins by estimating the time to closest approach and the projected miss distance using straight-line extrapolation. If both are small, then the logic determines that an alert is necessary. If an alert is necessary, the logic will model standard climb and descend maneuvers assuming a 5-second pilot response delay, followed by a 0.25 g acceleration. It chooses the direction that provides the greatest separation from the intruder. It then models a set of different advisory rates that are consistent with the chosen direction. TCAS chooses the lowest rate that provides a required amount of separation.

Although the general steps TCAS uses to select advisories are relatively straightforward, the details of the logic are very complex. Embedded in the TCAS logic specification are many heuristic rules and parameter settings designed to compensate for sensor noise and error as well as for variability in the pilot response. There are also rules that govern when to strengthen, weaken, and reverse advisories and how to handle encounters with multiple simultaneous intruder aircraft.

the logic was represented in earlier versions of TCAS. Instead of complicated rules that had to be translated into code and implemented, all of the complexity of the logic is represented in a table that can be standardized, certified, and given to manufacturers of the system. Updates can then be made to the system by generating the new table and uploading the table to aircraft, without having to change any code.

Figure 4 shows how the numeric lookup table is used in real time on board an aircraft. The system receives sensor measurements every second. On the basis of these sensor measurements, the system infers the distribution over the aircraft's current status. This status, or state estimation, takes into account the probabilistic dynamic model and the probabilistic sensor model. This state distribution determines where to look in the numeric

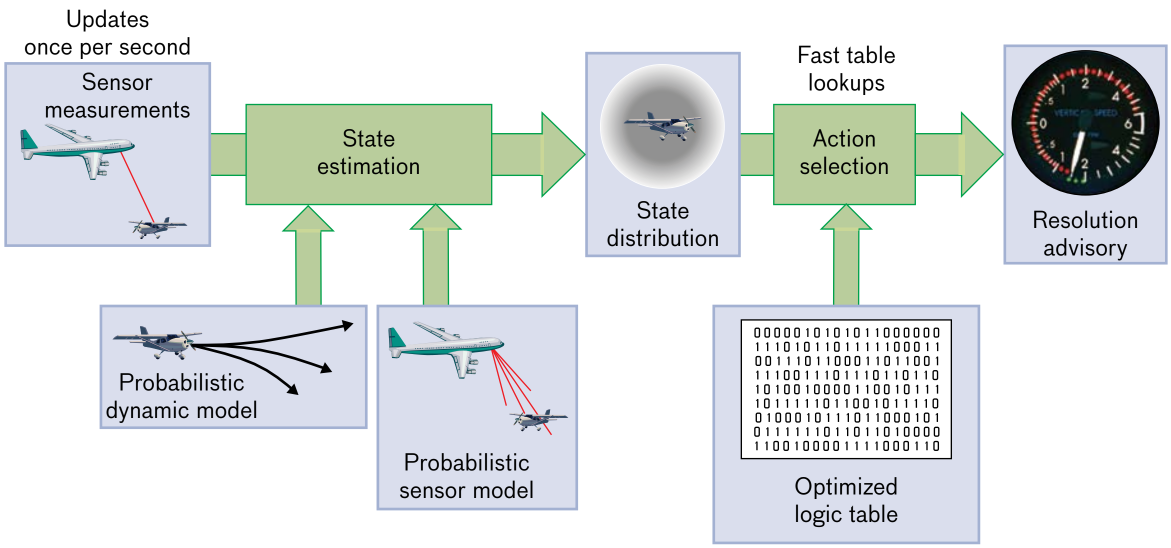



**FIGURE 4.** ACAS X performs state estimation and action selection once per second. Based on new sensor measurements and models of the dynamics and sensors, the system updates its estimate of the state of the aircraft. Uncertainty in the state estimate is represented as a probability distribution. This distribution specifies where to look in a table to determine which resolution advisory to provide to the pilots.

logic table to determine the best action to take—that is, whether to issue an advisory and if so, what vertical rate to use. This processing chain is repeated once per second with every new sensor measurement [8].

Critical to understanding the logic optimization process are two important concepts. The first is a Markov decision process, which is essentially the probabilistic dynamic model combined with the utility model. The second is dynamic programming, which is the iterative computational process used to optimize the logic.

### Markov Decision Processes

Markov decision processes (MDP) are a general framework for formulating sequential decision problems [9]. The concept has been around since the 1950s, and it has been applied to a wide variety of important problems. The idea is very simple, but the effective application can be very complex. Figure 5 shows a small MDP with three states, but to adequately represent the collision avoidance problem, as many as 10 million states may be required—the states representing the state of the aircraft involved, including its position and velocity.

Available from each state is a set of actions. In Figure 5, actions A and B are available from all three states. In the collision avoidance problem, the actions correspond to the various resolution advisories available to the system. Depending on the current state and the action taken, the next state is determined probabilistically. For example, if action A is taken from state 2 in the example MDP, there is a 60% chance that the next state will be 1 and a 40% chance the next state will be 2.

The benefits or rewards of any action are generated when transitions are made. Rewards can be positive, such as +1 and +5 in the example, or they can be negative like –10 for making the transition from state 3 to state 2 by action B. In the collision avoidance problem, there are large costs for near midair collisions and small costs for issuing resolution advisories to the pilots. There are also costs for reversing the direction of the advisory and increasing the required vertical rate. The objective in an MDP is to choose actions intelligently to maximize the accumulation of rewards, or, equivalently, minimize the accumulation of costs.

### Dynamic Programming

Dynamic programming is an efficient way to solve an MDP [10]. The first step involves discretizing the state space. Figure 6 shows a notional representation of the state space, where the discrete states are represented as boxes. In this simple representation, the vertical axis represents altitude relative to the other aircraft, and the horizontal axis represents time. The time at which a potential collision occurs corresponds to the rightmost column. The

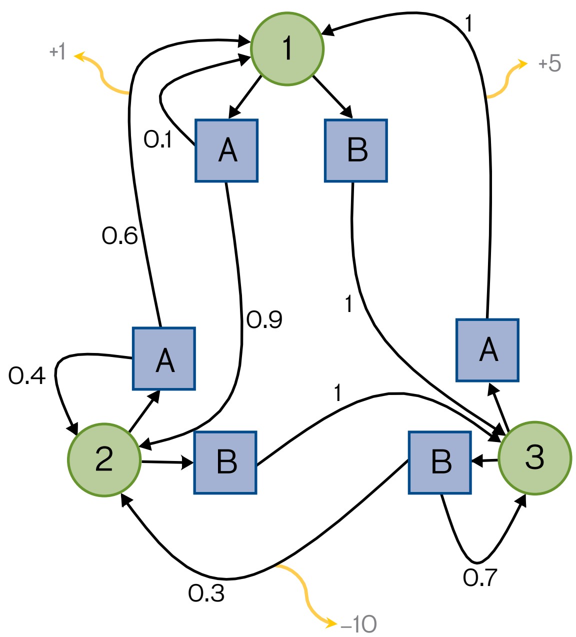



**FIGURE 5.** This simple, three-state system depicts the principal features of a Markov decision process. From each state, a decision must be made between action A or B. Depending on which action is selected, the system will transition to some new state according to the probabilities shown in the diagram. Rewards are assigned to certain transitions.

box at the center of the rightmost column corresponds to a collision. It is colored red in Figure 6 to indicate that the expected cost of that state is very high. The other boxes in that column are green because collision is avoided.

Figure 6a shows how to compute the expected cost at a state in the previous column by using the costs in the rightmost column. The probabilistic dynamic model is used to predict the state at the next time step for the various actions. The thickness of the arrows indicates the likelihood of the transition. In this case, if the climb action is executed, the aircraft will go one block up at the next time step, but some of the time it will go either two or zero blocks up. The expected cost of the climb action is just the cost of alerting added to the average of the costs of the next states weighted by their likelihood.

As shown in Figure 6b, the process is repeated for all the actions. The best action from that state is the one that provides the lowest expected cost. In this case, the climb and descend actions provide the same expected cost, and so we break the tie in favor of descending. The cost for that state becomes the cost for descending (Figure 6c). The process is repeated for the entire column (Figure 6d). Once that column is known, the costs for that column are propagated backwards, again using the probabilistic dynamic model (Figure 6e). The process completes when all the costs and best actions are known, as shown in Figure 6f.

The dynamic programming process implicitly takes into account every possible trajectory through the state space and its likelihood without having to enumerate every possible trajectory. The number of possible trajectories grows exponentially with the time horizon, and so it would not be feasible to enumerate every possible trajectory in even very simple models. In the collision avoidance MDP, the number of possible trajectories exceeds the number of particles in the universe, but dynamic programming can perform all the necessary computation in 10 minutes.

**Logic Plots**

One way to visualize the optimized logic is through plots like those shown in Figure 7 and Figure 8. These plots for a highly simplified model of collision avoidance are for illustration only, and so do not accurately reflect the actual behavior of ACAS X. Figure 7 assumes that the ACAS X–equipped aircraft and intruder, which may or may not be equipped with collision avoidance, are currently level. Figure 8 assumes that the ACAS X-equipped aircraft is climbing at 1,500 ft/min and the intruder is level. The vertical axis is the altitude of the ACAS X aircraft relative to the intruder, which stays fixed at 0. The horizontal axis is the time until potential collision. For example, in Figure 8, if the primary aircraft is 20 seconds away from potential collision and 200 ft below the intruder, then the optimal action is to descend.

Several interesting features of the optimal policy can be observed from these plots. As highlighted in red in Figure 7, the best action is to not alert when there are fewer than 5 seconds to potential collision. The reason for not alerting is the pilot response model used in optimization. This simplified example assumes that exactly 5 seconds are required for pilots to respond to their advisories. In reality, there is a chance that pilots might respond within 5 seconds, and so an alert could be helpful in preventing collision. If the model is adapted to allow for immediate responses, the alerting region moves to the right as expected. The actual model used to optimize the ACAS X logic assigns some probability to a wide variety of response delays, providing robustness to the variation of pilot response observed in the actual airspace [11].

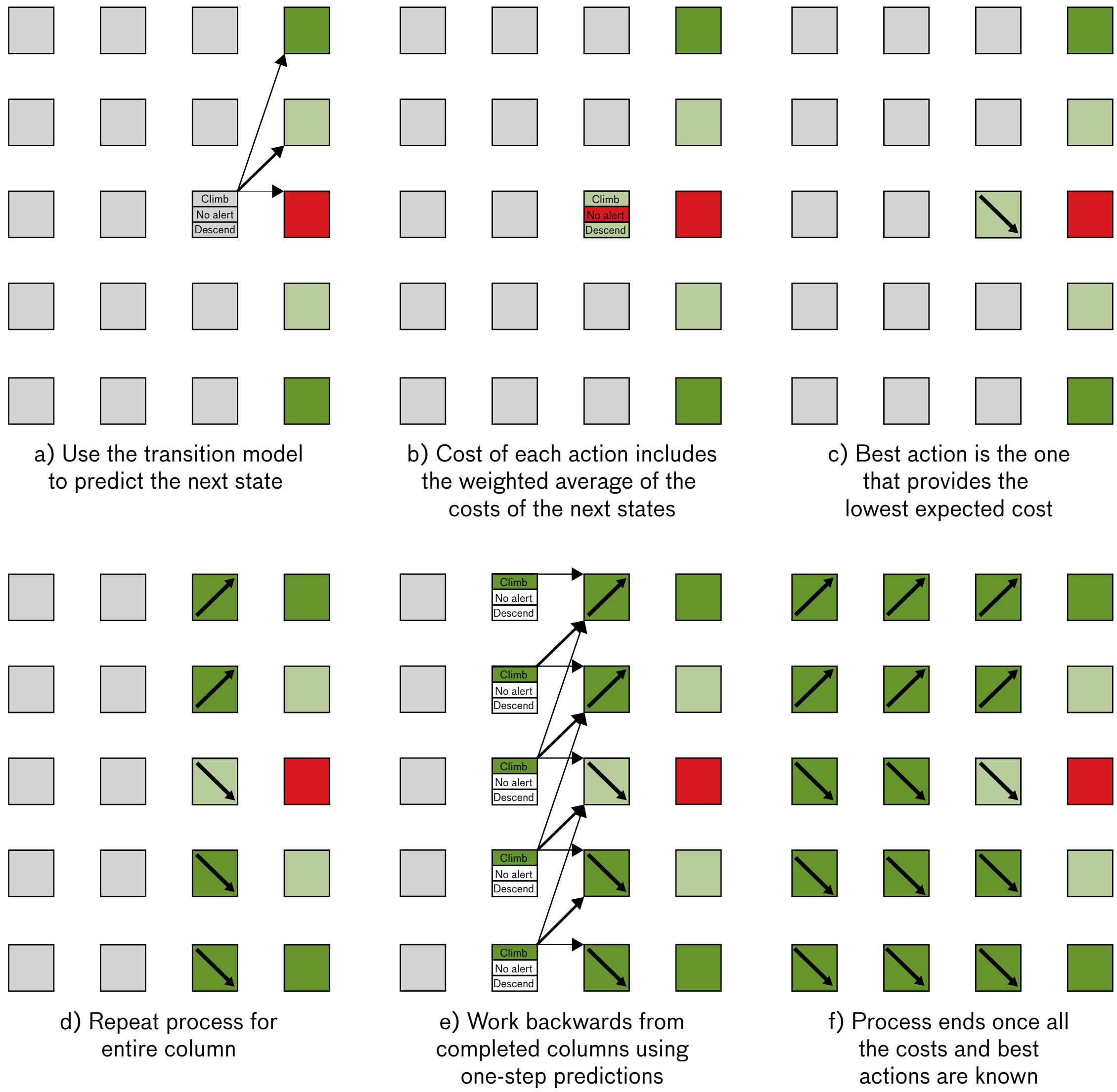



**FIGURE 6.** Dynamic programming is an incremental process for computing optimal actions from every state. In this diagram, the red state indicates a collision. The process works backwards from the time of potential collision.

There is another feature that was found surprising to many of the people who have been working on TCAS for many years. In Figure 7, there is a little notch in the alerting region where an alert is delayed. This notch reflects the fact that the optimization takes into account the uncertainty of where the aircraft will be in the future. When an intruder is nearly co-altitude, it may be best to wait to see whether the ACAS X aircraft ends up above or below the intruder. This delay helps prevent unnecessary alerts, and it helps prevent committing to a bad advisory that would later need to be reversed. The legacy TCAS logic does not implement this kind of delay.

Figure 8 looks different from Figure 7 because the ACAS X aircraft is climbing at 1,500 ft/min. One interesting feature of this plot is that in some cases where the ACAS X aircraft is below the intruder, it is best to climb. Climbing can be beneficial when there is insufficient time to descend and pass below the intruder.

## Surveillance

The current TCAS logic is tied to a particular type of beacon-based surveillance and makes strong assumptions about its error characteristics. In 2020, a government mandate of Automatic Dependent Surveillance–Broad-

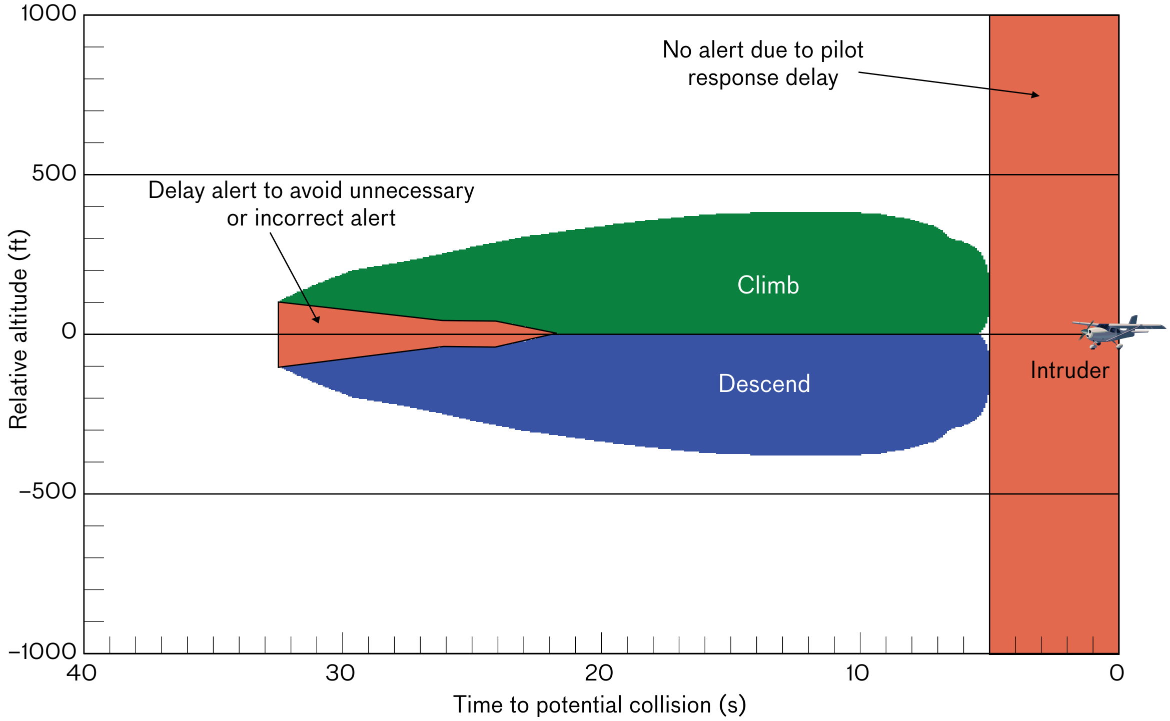



**FIGURE 7.** This diagram shows the optimal action to execute for a slice of the state space where both the ACAS X aircraft and the intruder are level.

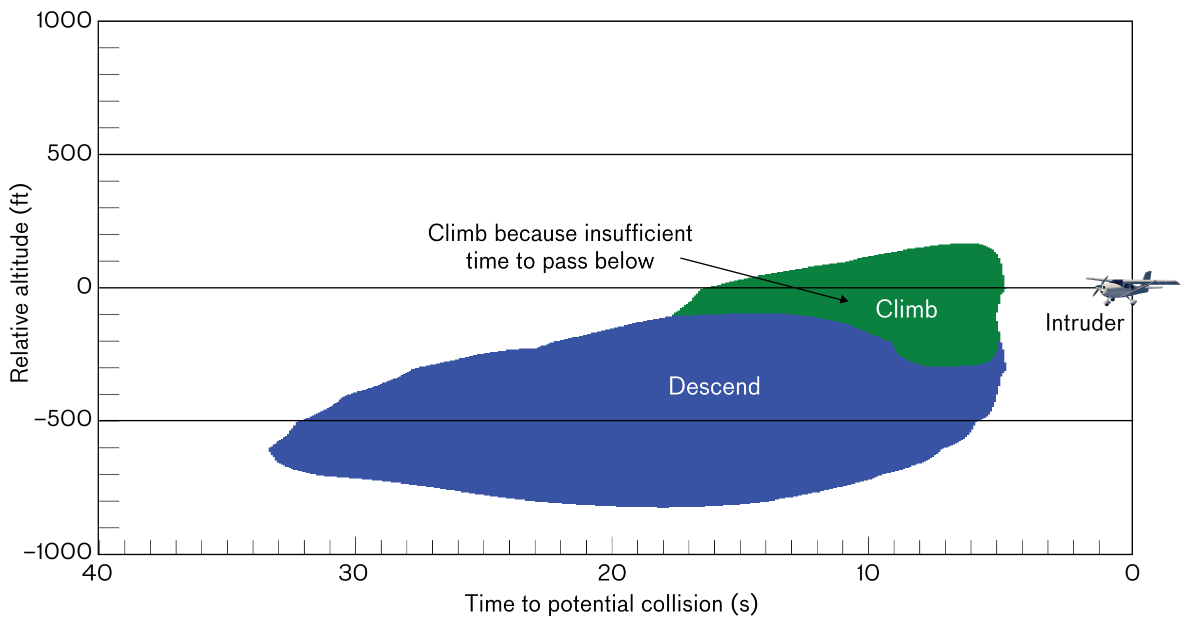



**FIGURE 8.** This diagram shows the optimal action to execute for a slice of the state space where the ACAS X aircraft is climbing at 1,500 ft/min and the intruder is level.

cast (ADS–B) will take effect, requiring the majority of aircraft in U.S. airspace to be equipped with high-integrity GPS units and to transmit updates of their location and other data. Some TCAS units have been modified to use ADS-B information, but its use is limited to assisting in tracking local air traffic. Well before an advisory is issued, TCAS switches to using beacon-based surveillance exclusively, preventing TCAS from benefiting from the full potential of highly precise ADS-B information.

Unlike the current TCAS logic, the ACAS X logic for generating resolution advisories is compatible with any surveillance source or combination of surveillance sources that meets specified performance criteria. The concept of plug-and-play surveillance will bring a number of benefits. Improved surveillance can lead to improved safety with fewer alerts. The ability to use surveillance sources other than the traditional beacon-based system will extend collision avoidance to new user classes. Small aircraft will be able to use ADS-B information broadcast by other aircraft for collision avoidance without having to be equipped with an expensive beacon-based surveillance system with significant power requirements. Unmanned aircraft that must be able to avoid aircraft not equipped with beacon transponders will be able to use electro-optical, infrared, and radar surveillance systems.

### Coordination

Different aircraft in an encounter can have different views of the situation because of sensor limitations. These differing views can lead to potentially incompatible maneuvers. For example, sensor limitations may lead both aircraft to issue climb advisories, which would increase the risk of an induced collision. During the development of TCAS, it became clear that an explicit coordination mechanism was necessary.

If an aircraft with TCAS gets an alert against another aircraft with TCAS, it will send a coordination message to the other aircraft instructing it to not climb or not descend, as appropriate. If both aircraft happen to select incompatible actions simultaneously, then the aircraft with the higher identification number is forced to reverse the direction of its advisory. In rare cases, such as an aircraft receiving instructions from different aircraft to not climb and not descend, it may be forced to level off.

The version of ACAS X intended for large commercial aircraft will adopt the same coordination mechanism as TCAS. Backwards compatibility with the existing TCAS system is necessary since ACAS X and TCAS will need to interoperate with each other for the foreseeable future. The version of ACAS X for small aircraft will need to adopt a different mechanism for coordination because it will not have the ability to send coordination messages over the same data link. Although the details for small aircraft coordination are still the subject of research, they will likely involve the population of coordination fields in ADS-B messages.

### Safety and Operational Validation

ACAS X must accommodate many operational goals and constraints while meeting the established safety requirements. It is important that the system provide effective collision protection without unnecessarily disrupting pilots and the air traffic control system. In addition to producing as few alerts as possible, it must issue advisories that resolve encounters in a manner deemed suitable and acceptable by pilots and the operational community.

The design of this new collision avoidance system is facilitated by fully studying the performance of the existing TCAS. As part of the FAA's TCAS Operational Performance Assessment (TOPA) program, the Laboratory has been involved in monitoring the performance of TCAS on the basis of data transmitted to the ground [12]. Analysis has shown that, although TCAS is an effective system operating as designed, it currently issues alerts in situations where aircraft are legally and safety separated. In some situations, more than 80% of TCAS alerts occur during normal procedures that do not represent a collision risk.

Figure 9 shows results from more than four years of U.S. TCAS performance monitoring. As the chart indicates, TCAS generated alerts during different types of normal and safe operations. In rare instances, these advisories are generated because of pilot or air traffic control blunders. ACAS X aims to address specific incompatibilities of the current TCAS logic and the current and planned airspace procedures.

The safety and operational validation of ACAS X involves establishing the required performance metrics and models used to generate the test scenarios to evaluate the logic. After deciding on the metrics and models, the safety logic is tuned to meet safety and operational requirements. With each iterative improvement to the safety logic, the performance of the system is reassessed. The tuning pro-

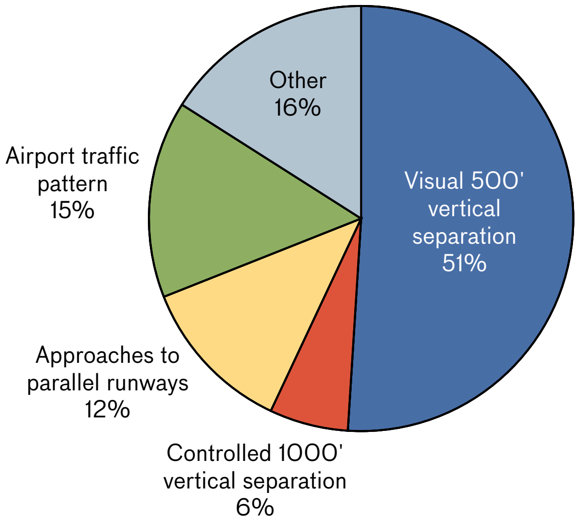



**FIGURE 9.** This plot shows resolution advisory events recorded in the United States over several years. Most advisories are issued during normal and safe operations.

cess may result in the development of additional metrics and models. Individual encounter situations are examined to ensure that the system performs as expected.

### Models and Data

The test scenarios used to evaluate the logic are generated from several different sources.

**1. Operational radar data.** Radar surveillance from over 100,000 real aircraft encounters that resulted in TCAS alerts in current airspace is provided from TOPA monitoring data. These aircraft trajectories are replayed with the new logic to assess how it would work in operationally relevant situations, and the results are then compared with the baseline TCAS logic performance. The data allow us to estimate the benefits or operational impact resulting from the new system in today's airspace and operations.

**2. Airspace encounter models.** Because near midair collisions occur so rarely in the airspace, it is difficult to accurately estimate their occurrence in simulations based on radar data. Historically, airspace encounter models have been used to estimate collision risk by generating a large collection of encounters that are statistically representative of the airspace [13]. With funding from the FAA, Lincoln Laboratory recently developed a high-fidelity model of the U.S. airspace based on a large amount of radar data [14].

**3. Procedure-specific models.** Several models have been developed to help evaluate safety logic performance under specific intentional procedures, such as approaches to closely spaced parallel runways. These procedures may be simulated to match nominal conditions or may have artificially injected pilot blunders and air traffic controller errors. Simulations using these models facilitate a wide range of possible setups and perturbations of relevant scenarios that are unlikely to be observed with enough frequency to be statistically relevant without decades of data collection.

**4. Stress-testing models.** Historically, stress testing was performed on TCAS logic versions to ensure adequate performance during very unlikely, but difficult to resolve, encounters. The encounters were based on aircraft trajectory pairs recorded in the airspace prior to the introduction of TCAS and were modified to span and exceed the parameters observed in the radar data. The new ACAS X logic is being assessed with these same encounters.

### Metrics

The performance of the logic is assessed using metrics related to safety, operational suitability, and acceptability. The ACAS X development team from several organizations collaborated to capture the relevant TCAS design requirements, along with the motivations for selecting them. The team also reflected on operational lessons learned that helped shape the current TCAS logic [15].

Key metrics for operational suitability and pilot acceptability include minimizing the frequency of alerts that result in reversals or intentional intruder altitude crossings, both of which may lead to pilot confusion or mistrust if not obviously needed for safe encounter resolution. Also desired is minimizing the frequency of disruptive advisories in noncritical encounters. These metrics were important in the design of TCAS and continue to be important for ACAS X.

Another metric compares the initial vertical rate of the advisory to the current rate. One goal is to minimize the difference between these while still providing effective, safe resolution of an encounter. A collision avoidance system could be tuned to maximize the separation from a potential threat, but this may result in a secondary conflict with another aircraft. Additionally, excessive deviations from current trajectories increase pilot and air traffic controller workload.

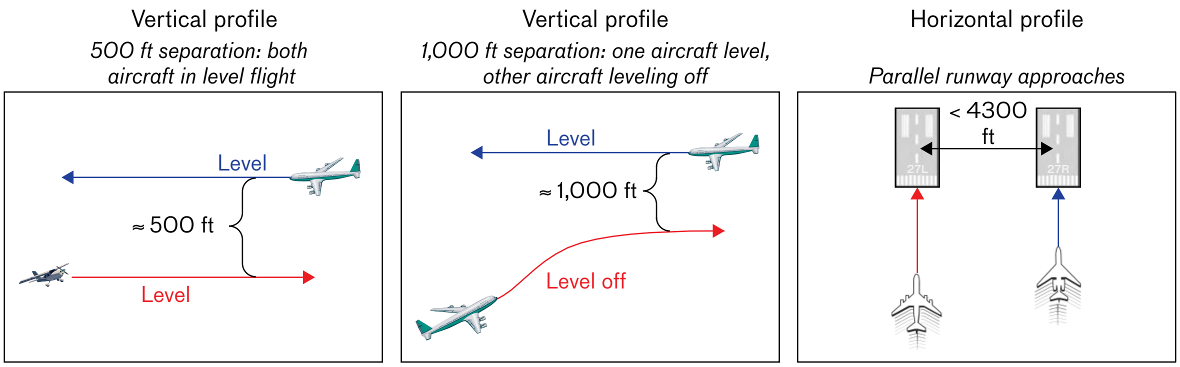



**FIGURE 10.** Shown here are the three main encounter types representing the majority of U.S. TCAS alerts.

In addition to high-level design goals, three procedures in use are challenging for collision avoidance systems because of a lack of information aabout pilot and air traffic controller intentions. Both TOPA encounters and procedure-specific encounters allow these operations to be assessed. These procedures, comprising almost 70% of the TCAS alerts illustrated in Figure 9, are summarized below and are illustrated in Figure 10.

**1. Encounters with 500 ft vertical separation.** In these procedures, two aircraft are flying level in visual conditions with 500 ft vertical separation. The goal is either to not alert or to provide preventive-only guidance to pilots, such as "Do not climb" or "Do not descend." These advisories are expected to better match the pilots' intentions.

**2. Encounters with 1,000 ft vertical separation.** In these procedures, two aircraft are flying under instrument flight rules with 1,000 ft vertical separation. The aircraft are flying level or leveling off. Issuing alerts that cause significant vertical rate deviations is discouraged. When it is necessary to alert, it is preferable to issue minimally disruptive guidance, such as a "level off," which pilots likely intend to do in the absence of an alert.

**3. Closely spaced parallel departures and approaches.** In these procedures, two aircraft depart from or approach closely spaced parallel runways. The intent is to eliminate or minimize resolution advisories during non-conflict parallel departures and approaches, and only issue alerts if a blunder occurs that compromises safety.

## Performance Tuning

The optimization process used by ACAS X accommodates high-level safety and operational objectives. Throughout the validation process, the expert team provides either target rates for certain metrics or high-level recommendations, such as minimizing reversal advisories.

This optimization was conducted in an iterative manner with a test logic version that was run through all four validation models and data sets. The results were assessed and compared with current TCAS performance and against the established operational and safety design goals. The next desired modifications were then prioritized and specified by the team for the next tuning phase. After modifications were made to the logic and there was evidence that the concerns were addressed, new simulation runs were executed and the assessment was repeated.

The process of assessment, recommendations, tuning, and reassessment was used over six specific data runs and resulted in improved suitability. While much improvement has been observed, there are more comprehensive stress testing and new human-in-the-loop studies that may influence additional logic changes.

## Results

As a result of extensive tuning both for safety and operational suitability, key assessment results show that, in comparison with TCAS, ACAS X reduces collision risk by 47%, reduces the overall alert rate by 40%, and issues 56% and 78% fewer alerts in the intentional 500 ft and 1,000 ft encounter scenarios, respectively. Figure 11 shows these comparative results in graphical form. From identical encounters provided by simulation, ACAS X issued 23,481 and 1,579 fewer advisories, respectively, for 500 ft and 1,000 ft encounters. The risk ratio, representing the probability of a near midair collision with a collision avoidance system divided by the probability without, shows that ACAS X improves safety by 54%.

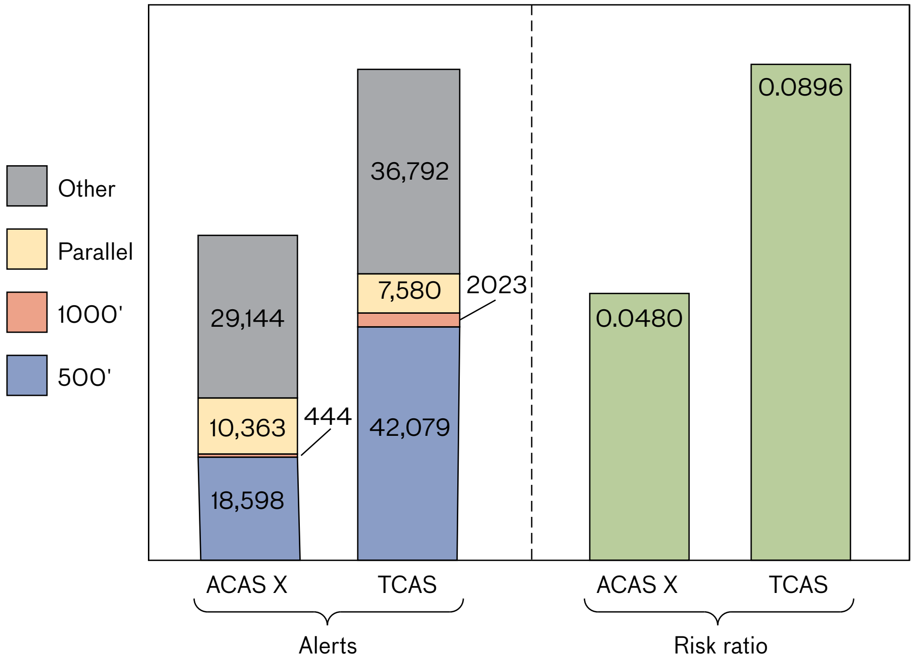



**FIGURE 11.** An evaluation of the ACAS X safety and operational performance relative to TCAS shows fewer unnecessary alerts were generated by ACAS X. In addition, the risk ratio is significantly reduced compared to TCAS.

One area where ACAS X still needs improvement is in the parallel approach encounter category. ACAS X issued 38% (2,783) more advisories than did TCAS. ACAS X does not do as well as TCAS in these encounters because of the model used to optimize the safety logic. Parallel approaches were not explicitly modeled because, though they are close maneuvers, they do not represent significant risk except in cases of human error. Adapting ACAS X logic for parallel approach operations is the subject of ongoing research and may require additional information from the adjacent aircraft. This adaptability demonstrates another advantage of ACAS X, the ability to provide operation-specific treatment of aircraft on adjacent runway approaches while providing global protection against other aircraft.

Additional benefits of ACAS X are noted in high-traffic-density regions. For example, in the terminal airspace encompassing all the major airports in the New York City and Newark, New Jersey, areas, TCAS currently issues advisories under normal procedures. Many of the advisories occur when visual acquisition is used for separation. ACAS X cuts the number of advisories in half, as shown in Figure 12.

**Example Encounter**

On the basis of statistical results obtained through simulation, experts were asked to prioritize and evaluate a subset of interesting encounters. Of particular interest were reversal and crossing advisories because they are intended to occur infrequently. In some cases, however, TCAS issued crossing and reversal advisories sequentially in the encounter even though TCAS has many heuristic rules biasing it against these alerts. In contrast, ACAS X was able to resolve these encounters much more suitably. Figure 13 shows the vertical aircraft trajectories of an example encounter in which TCAS issued an initial crossing descend advisory, followed by a reversal to a climb and a weakening advisory. Figure 14 shows that same encounter with the advisory issued by ACAS X.

In this encounter example, ACAS X resolved the encounter with a simple preventive “Do not descend” advisory. The ACAS X advisory sequence was simpler and less disruptive for the flight crew than the TCAS advisory. Since this encounter is an intentional 500 ft level off/level off encounter geometry, it was more suitable for ACAS X to restrict a descent, which the flight crew likely did not intend to do anyway, rather than issue

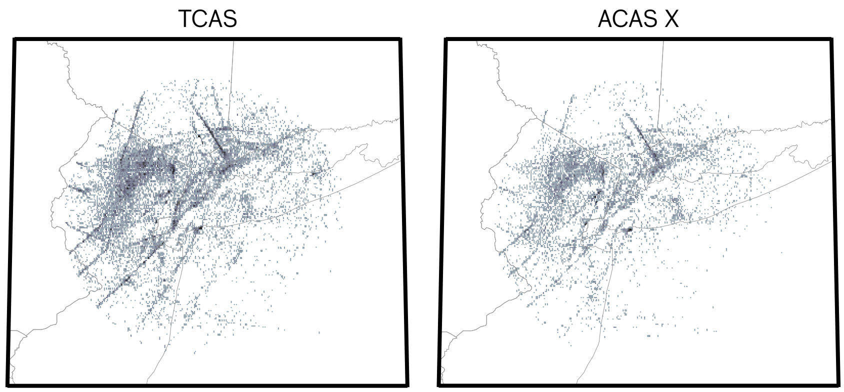



**FIGURE 12.** Compared with TCAS, ACAS X reduces the number of advisories by half, as shown in these plots of alerts in the greater New York City metropolis taken over a multiyear period.

a climb as TCAS did. Since ACAS X did not cause pilots to deviate from their intentions, this alert would be more acceptable in light of both pilot workload and the overall air traffic system.

## Flight Test

Because of the successful development of the ACAS X threat logic, the FAA is planning an initial proof-of-concept flight test in 2013. This flight test will be conducted with the ACAS X threat resolution logic coupled with current TCAS surveillance and hardware, and is intended to demonstrate that

- The ACAS X logic functions as designed and tested in modeling and simulation.
- The software architecture and associated processing are feasible for operational use.
- The alerts or lack thereof are deemed suitable and acceptable by the flight crews and other operational users.

The FAA has contracted with one of the current TCAS manufacturers to integrate the new ACAS X threat logic into the existing hardware unit. This manufacturer will deliver a prototype unit that performs the same functions as the current certified system, including air-to-air surveillance, advisory coordination, and pilot interface. By preserving the legacy surveillance, the outcomes of the flight test will show the performance differences based solely on the new safety logic.

Lincoln Laboratory is planning and coordinating the flight test, which will be flown by the FAA's William J. Hughes Technical Center in Atlantic City, New Jersey. During the flight test, one of the Technical Center aircraft will have the current TCAS removed and replaced by the prototype ACAS X unit. This ACAS X aircraft will then be flown in preplanned encounters with intruder aircraft also supplied by the Technical Center. Some intruders will not have collision avoidance, while others will be equipped with a legacy version of TCAS.

The encounter scenarios will be selected and prioritized on the basis of operational relevance and will include two groups: (1) conflict situations where advisories are anticipated and desired, and (2) normal procedures (non-conflicts) where advisories are either not anticipated or designed to have minimal impact. Anticipated scenarios for the flight test include the 500 ft and 1,000 ft vertical separation encounters discussed earlier, non-conflict vertical situations, and altitude crossing scenarios. More complex scenarios include planned blunders in the above scenarios, close but offset setups emulating conflict encounters, forced reversals, closely spaced parallel approaches and departures, and coordinated encounters with legacy TCAS.

Data that will be collected from onboard instrumentation as well as ground-based sensors include

- Surveillance and safety logic data from the ACAS X and TCAS units
- Position and other truth data from each aircraft
- Airborne and ground recordings of surveillance messages
- Ground radar data, including the downlinks recorded when an aircraft reports an advisory
- Cockpit data, which may include audio and visual recordings of the TCAS traffic display, vertical speed indicators, and audio alert annunciations
- Test pilots' live reactions and comments during the encounters

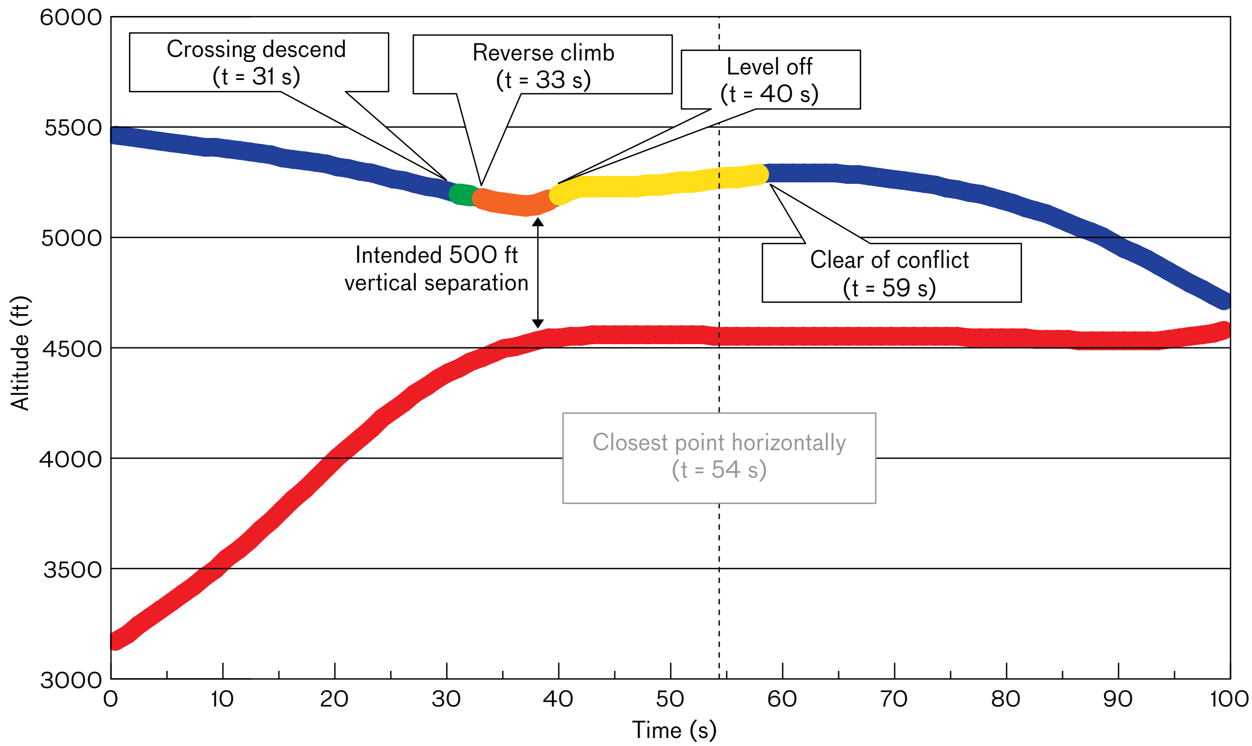



**FIGURE 13.** The TCAS alert sequence for this typical example encounter illustrates an initial altitude crossing advisory, followed by a reversal, both of which are undesirable in this situation.

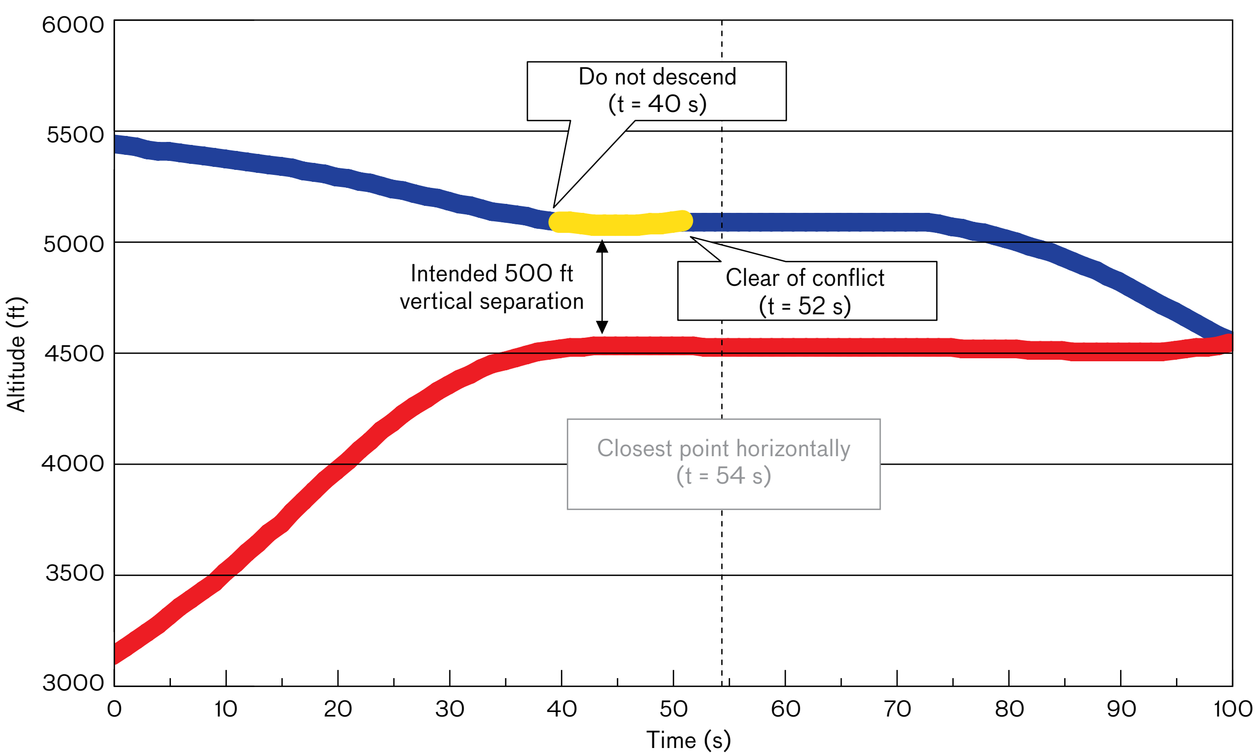



**FIGURE 14.** In the same example encounter as noted for TCAS in Figure 13, the ACAS X alert sequence is reduced to one single preventive advisory ("Do not descend"), which is minimally disruptive to pilots and likely matches their intentions.

Post-flight-test tasks will include comprehensive assessment of the performance of ACAS X, the legacy TCAS surveillance and its impact on the resulting ACAS X alerts, and all the data collected during the encounters. In addition to assessing ACAS X performance, researchers will be conducting a comparative analysis of the TCAS logic under the same inputs and using simulations after the flights. If the ACAS X logic meets expectations under the live flight-test conditions, there will be substantial evidence that the proof of concept is valid and that the new logic will work in a way that is operationally acceptable.

## Road Ahead

One of the most exciting extensions of the ACAS X program is the application to unmanned aircraft, which have different performance capabilities and rely upon different surveillance systems from traditional TCAS aircraft. A sense-and-avoid capability is required for the routine access of unmanned aircraft to civil airspace. Sense-and-avoid involves both collision avoidance and self-separation. Self-separation means maintaining a safe distance from other aircraft without triggering collision avoidance of the other aircraft. Self-separation maneuvers may require heading and speed changes. ACAS X is focused on the collision avoidance aspect, but the same idea of using Markov decision processes and dynamic programming has been extended to self-separation. The development of these algorithms has led to programs sponsored by the Army, Air Force, and the Department of Homeland Security for ground-based and airborne systems.

Another research area is the development of a procedure- or environment-specific implementation of the logic, since future airspace may utilize reduced separation standards to increase efficiency. This procedure-specific functionality would allow alerting that is tailored for selected aircraft by using an individualized lookup table while providing collision avoidance protection against other traffic. This functionality would even benefit today's procedures, such as those for parallel approaches, during which incompatible alerts necessitate some operators to turn off the resolution advisory function of TCAS to prevent interference from frequent alerts. In such cases and others, this functionality would ensure optimal collision avoidance protection against another aircraft's blunders or other intruding traffic while causing minimal interference from unnecessary advisories.

Lincoln Laboratory is actively researching the application of this collision avoidance logic concept for small aircraft. The ease of optimization may facilitate the development of logic for aircraft that have lower performance capabilities and operational needs and limitations different from those of the existing aircraft using TCAS. The Laboratory is also leading the surveillance research area and is developing an interface and tracker that will allow a variety of inputs to be plug-and-play with the optimized threat logic.

The regulatory effort required for both U.S. and international acceptance and certification of ACAS X is intensive but has already begun. Domestically, the federal advisory committee, the Radio Technical Commission for Aeronautics, or RTCA, has been briefed in detail on ACAS X. International outreach efforts have included briefings and interactions with the joint European aviation governing body. ACAS X has also gained substantial visibility across key departments within the FAA that will further aid the remaining development and anticipated certification and mandate.

## Acknowledgments

The ACAS X program is led by FAA TCAS program manager Neal Suchy, who recognized the potential of this new safety logic and structured a program to pursue it. The Lincoln Laboratory ACAS X program has been managed by Wes Olson, also a key contributor to its concept development and performance analyses, and overseen by Gregg Shoults. The dedicated team responsible for the success of ACAS X includes Dylan Asmar, Tom Billingsley, Barbara Chludzinski, Ann Drumm, Tomas Elder, Leo Javits, Adam Panken, Chuck Rose, Dave Spencer, and Kyle Smith. Many of the important concepts underlying ACAS X were developed in collaboration with Leslie Kaelbling, Tomas Lozano-Perez, and Selim Temizer at the MIT Computer Science and Artificial Intelligence Laboratory. The authors also gratefully acknowledge the important contributions and collaborations spanning several organizations. ■

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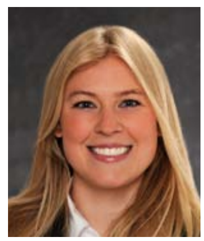

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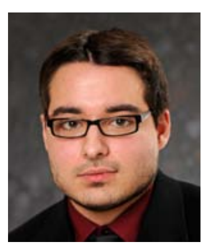

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