The Traffic Alert and Collision Avoidance System

James K. Kuchar and Ann C. Drumm

The Traffic Alert and Collision Avoidance System (TCAS) has had extraordinary success in reducing the risk of mid-air collisions. Now mandated on all large transport aircraft, TCAS has been in operation for more than a decade and has prevented several catastrophic accidents. TCAS is a unique decision support system in the sense that it has been widely deployed (on more than 25,000 aircraft worldwide) and is continuously exposed to a high-tempo, complex air traffic system. TCAS is the product of carefully balancing and integrating sensor characteristics, tracker and aircraft dynamics, maneuver coordination, operational constraints, and human factors in time-critical situations. Missed or late threat detections can lead to collisions, and false alarms may cause pilots to lose trust in the system and ignore alerts, underscoring the need for a robust system design. Building on prior experience, Lincoln Laboratory recently examined potential improvements to the TCAS algorithms and monitored TCAS activity in the Boston area. Now the Laboratory is pursuing new collision avoidance technologies for unmanned aircraft.

A collision between aircraft is one of the most sudden and catastrophic transportation accidents imaginable. These tragic events are rarely survivable—hundreds of people may die as the two aircraft are destroyed. In response to this threat, Lincoln Laboratory has been pursuing surveillance and alerting system technologies to protect aircraft operations both on the ground and in the air. Recent developments in the Runway Status Lights Program, for example, greatly reduce airport-surface collision risk due to runway incursions [1]. In the air, other systems have been developed and are currently in use to prevent mid-air collisions. This article focuses on the widely fielded, crucial technology called the Traffic Alert and Collision Avoidance System (TCAS). In the context of integrated sensing and decision support, TCAS illustrates the particular challenge of developing effective decision aids for use in emergency situations involving extreme time pressure.

Despite the terrifying prospect of a mid-air collision, aviation travel is incredibly safe. A person who flew continuously on a jet transport aircraft in today's environment could expect to survive more than 11,000 years of travel before becoming the victim of a mid-air collision. This accomplishment has only recently been realized. As shown in Figure 1, the number of hours flown annually by jet transport aircraft has more than quadrupled since 1970, but the rate of mid-air collisions over that period of time has dropped by an order of magnitude. The result is that today we can expect one mid-air collision every 100 million flight hours. Such an exceptional safety level was achieved through advances in air traffic surveillance technology and relentless attention to improving operational procedures. But as the September 2006 mid-air collision between a Boeing 737 and an Embraer Legacy 600 business jet over the Amazon jungle in Brazil demonstrates, maintaining safety is an ever present challenge. This challenge has been eased, but not eliminated, with the development and deployment of TCAS.

TCAS is one component of a multi-layered defense against mid-air collisions. The structure of airspace and

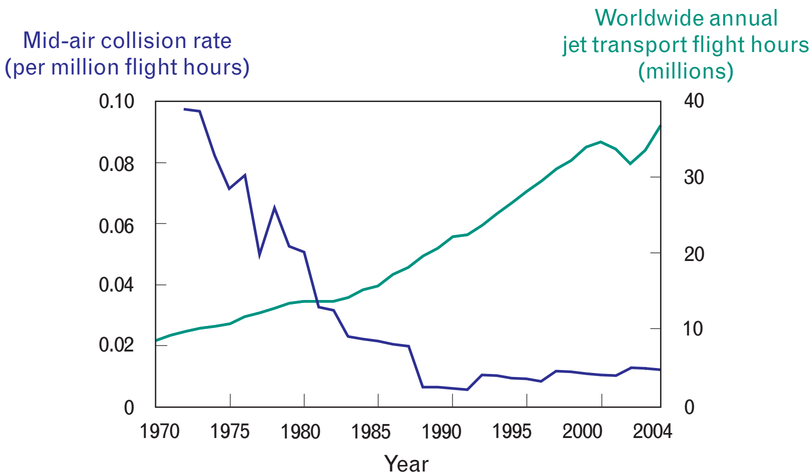

FIGURE 1. Worldwide annual flight hours and mid-air collision rate (collision rate based on a ten-year moving average). Flight hour data are from Boeing.

operational procedures provide the first, strategic layer of protection. Traffic flows are organized along airways at segregated altitudes to aid air traffic controllers (ATC) in managing aircraft and predicting potential conflicts well before problems arise. Aircraft are normally kept three to five miles apart laterally or 1000 ft vertically, to provide sufficient safety margins. Air traffic control ensures that separation minima are not violated by issuing tactical commands (including altitude restrictions and heading change vectors) to the pilots in response to nearby traffic. Should these nominal traffic separation processes fail, the TCAS system aids pilots in visually acquiring potential threats and, if necessary, provides last-minute collision avoidance guidance directly to the flight crew.

It is obviously imperative that TCAS alert the flight crew early enough that evasive action can be taken. But it is also important that TCAS not alert unnecessarily. Collision avoidance alerts represent high-stress, time-critical interruptions to normal flight operations. These interruptions, in addition to distracting the aircraft's crew, may lead to unnecessary maneuvering that disrupts the efficient flow of traffic and may over time also cause pilots to distrust the automation.

This article outlines some of the challenges in achieving this balance. A critical aspect is the need to accurately model sensors, system dynamics, and human involvement in the collision avoidance process. The wide deployment of TCAS provides a wonderful opportunity to collect feedback on performance and to understand the environment in which the system operates. It also highlights the fact that TCAS does not operate in a vacuum and any technological progress needs to mesh into a continuously operating environment.

History

Interest in development of a collision avoidance system dates back to at least the mid-1950s, when a mid-air collision occurred between two U.S. air carrier aircraft over the Grand Canyon. For several decades thereafter, a variety of approaches to collision avoidance were explored, until 1974, when the Federal Aviation Administration (FAA) narrowed its focus to the Beacon Collision Avoidance System (BCAS), a transponder-based airborne system. In 1978, a second mid-air collision occurred near San Diego between an air carrier and a general-aviation aircraft, leading to the expansion of the BCAS effort; in 1981, the name was changed to the Traffic Alert and Collision Avoidance System (TCAS). A third mid-air collision in 1986 near Cerritos, California, prompted Congress in 1987 to pass legislation requiring the FAA to implement an airborne collision avoidance system by the end of 1992. The mandate applied to all large (more than 30 passenger seats) turbine-powered aircraft in the United States. A subsequent law extended the original deadline by one year to the end of 1993. The first commercial TCAS systems began flying in 1990.

Monitoring and safety assessments led to a series of changes resulting in an international version of TCAS—referred to as Version 7, or the Airborne Collision Avoidance System (ACAS). Starting in January 2003, the International Civil Aviation Organization mandated the use of ACAS worldwide for all turbine-powered aircraft with passenger capacity of more than 30 or with maximum take-off weight exceeding 15,000 kg. In January 2005, that mandate was extended to cover aircraft with more than 19 passenger seats or maximum take-off weight of more than 5700 kg. Today, more than 25,000 aircraft worldwide are equipped with TCAS.

Lincoln Laboratory's involvement in BCAS/TCAS dates back to 1974, when the FAA tasked the Laboratory to develop the surveillance subsystem and MITRE Corp. to develop the collision avoidance algorithms, also known as the threat logic. Lincoln Laboratory's sur-

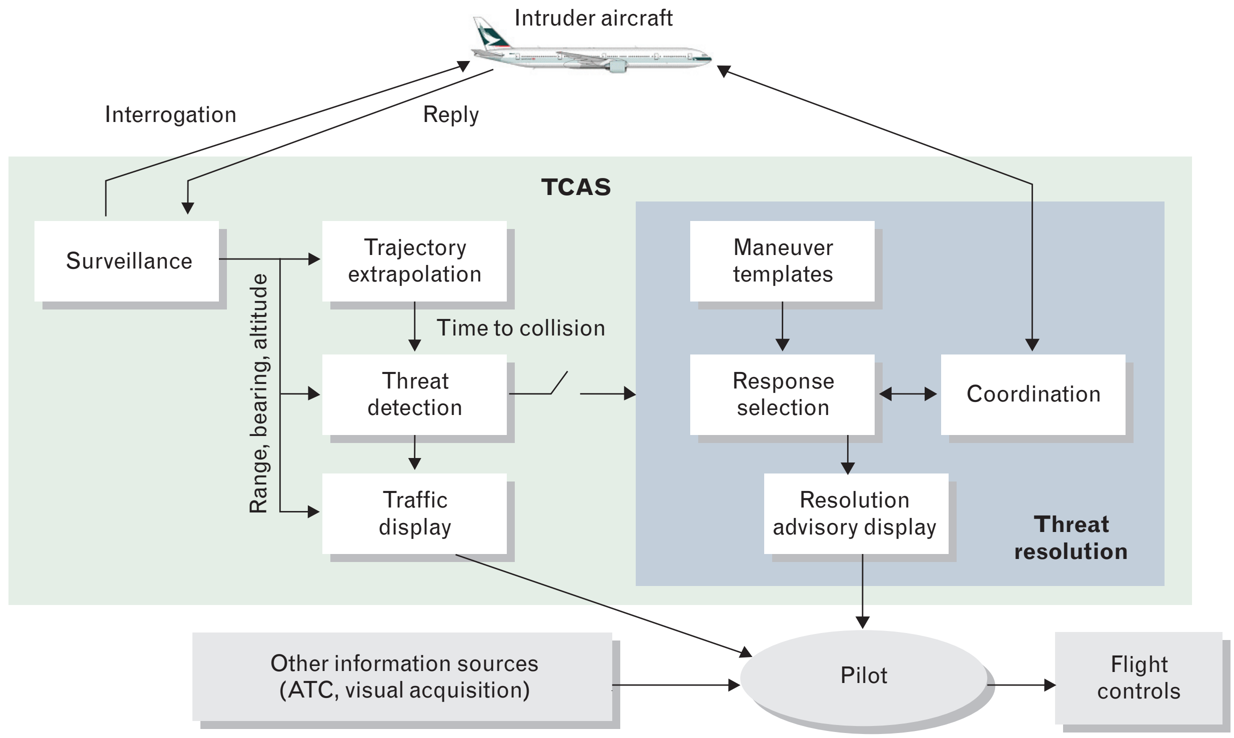

FIGURE 2. TCAS relies on a combination of surveillance sensors to collect data on the state of intruder aircraft and a set of algorithms that determine the best maneuver that the pilot should make to avoid a mid-air collision.

veillance activities continued throughout the next three decades; significant development took place during the BCAS-to-TCAS transition and during the design of TCAS Version 7 [2].

Lincoln Laboratory was involved in two additional TCAS activities besides surveillance development. In the mid-1970s the Laboratory, using first a Lincoln Laboratory–developed prototype Mode S sensor and then FAA production Mode S sensors, began TCAS-related monitoring of aircraft in the Boston airspace. Early monitoring focused on identifying transmitted data errors that would impact the performance of a collision avoidance system, such as garbled aircraft-reported altitude. Later monitoring focused on assessing the appropriateness of collision avoidance advisories and the impact of these advisories on airspace operation.

In the mid-1990s, the Laboratory undertook a third area of activity—assessing the threat logic. Because of the growing complexity of the threat logic, Lincoln Laboratory and the FAA William J. Hughes Technical Center began developing simulation and analysis tools to perform specific types of threat-logic assessment. This work was a precursor to the much more complex Lincoln Laboratory simulation tool that we describe later.

How TCAS Works

TCAS processes are organized into several elements, as shown in Figure 2. First, surveillance sensors collect state information about the intruder aircraft (e.g., its relative position and velocity) and pass the information to a set of algorithms to determine whether a collision threat exists. If a threat is identified, a second set of threat-resolution algorithms determines an appropriate response. If the intruder aircraft also has TCAS, the response is coordinated through a data link to ensure that each aircraft maneuvers in a compatible direction. Collision avoidance maneuvers generated and displayed by TCAS are treated as advisories to flight crews, who then take manual control of the aircraft and maneuver accordingly. Pilots are trained to follow TCAS advisories unless doing so would jeopardize safety. The following sections provide more detail on the methods used to perform surveillance, threat detection, and threat resolution.

Surveillance

Surveillance of the air traffic environment is based on air-to-air interrogations broadcast once per second from antennae on the TCAS aircraft using the same frequency (1030 MHz) and waveform as ground-based air traffic control sensors [3]. Transponders on nearby intruder aircraft receive these interrogations and send replies at 1090 MHz. Two types of transponders are currently in use: Mode S transponders, which have a unique 24-bit identifier, or Mode S address, and older Air Traffic Control Radar Beacon System (ATCRBS) transponders, which do not have unique addressing capability. To track ATCRBS intruders, TCAS transmits "ATCRBS-only all-call" interrogations once per second; all ATCRBS aircraft in a region around the TCAS aircraft reply. In contrast, Mode S–equipped intruders are tracked with a selective interrogation once per second directed at that specific intruder; only that one aircraft replies. Selective interrogation reduces the likelihood of garbled or overlapping replies, and also reduces frequency congestion at 1030/1090 MHz.

Replies from most ATCRBS and all Mode S transponders contain the intruder's current altitude above sea level. TCAS computes slant range on the basis of the round-trip time of the signal and estimates the bearing to the intruder by using a four-element directional antenna. Alpha-beta and non-linear filters are used to update range, bearing, and altitude estimates as well as to estimate range rate and relative-altitude rate. Mode S transponders also provide additional data-link capabilities. All aircraft with TCAS are equipped with Mode S transponders so that this data link can coordinate collision avoidance maneuvers.

One of the most difficult challenges in the development of TCAS is balancing the surveillance requirements of TCAS and air traffic control ground sensors—in particular, managing their shared use of the 1030/1090 MHz frequencies. As the density of TCAS-equipped aircraft grows, transponders in an airspace are interrogated by more and more TCAS units. As a result, transponders now devote more of their time to responding to TCAS and less of their time responding to ground interrogations. Because of concerns about frequency congestion, TCAS uses interference-limiting algorithms to reduce competition between TCAS and ground sensors. Each second, TCAS determines the number and distribution of other TCAS units in its vicinity. With that information, TCAS can reduce its maximum transmit power (i.e., reduce its surveillance range)—limiting the impact on the victim transponders and, in turn, on the ground sensors.

National and international requirements in this area are quite strict. Interference limiting is intended to ensure that for any given transponder, no more than 2% of its available time is consumed in communications with all nearby TCAS units. Because TCAS requires a minimum surveillance range to provide adequate collision avoidance protection, however, a limit is imposed on how much the TCAS transmit power can be reduced. As a result, it is possible for a transponder to exceed the 2% utilization figure in high-density airspace. Transponder utilization due to TCAS has been the focus of worldwide monitoring, and monitoring results continue to motivate the development of innovative TCAS surveillance techniques. Many such techniques were developed for Version 7, including using Mode S interrogation schemes that are different for distant, non-threatening intruders than for potential threats, and transmitting sequences of variable-power ATCRBS interrogations to reduce garble, or overlap, among concentrations of ATCRBS

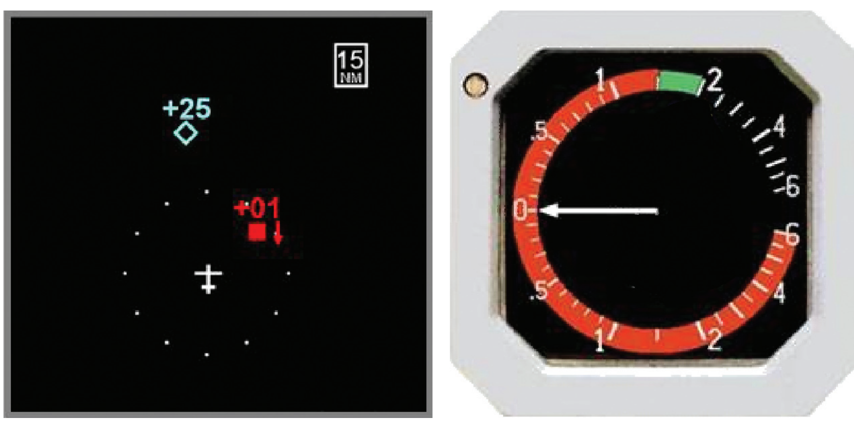

FIGURE 3. TCAS is an advisory system—i.e., it tells the pilot what to do to avoid collision but does not take control of the aircraft. Here, a TCAS traffic display (left) indicates that a threatening intruder aircraft is approximately 14 nautical miles ahead and to the right of the TCAS aircraft; this aircraft is 100 ft above the TCAS aircraft and is descending. A second, non-threatening intruder aircraft located about 22 nautical miles ahead is flying level 2500 ft above the TCAS aircraft. The Resolution Advisory (RA) display (right) indicates that the aircraft is flying level (i.e., vertical speed of 0). TCAS is instructing the pilot to climb at a rate of 1500 to 2000 ft/min, as shown by the green arc. The red arc on the display indicates vertical rates that do not comply with the RA.

intruders. In addition, standards are nearing completion for TCAS Hybrid Surveillance. This is a new technique that allows TCAS to make use of passive (Automatic Dependent Surveillance–Broadcast, or ADS-B) transmissions, thereby reducing TCAS interrogation rates.

Two other issues affect the ability of TCAS to track intruders. First, some older transponders do not report altitude information when interrogated. TCAS can not generate collision avoidance commands against these threats. (Large aircraft, aircraft flying in the vicinity of large airports, and aircraft flying above 10,000 ft are required to be equipped with altitude-reporting transponders.) Second, aircraft without a functioning transponder cannot be detected or tracked by TCAS at all. Some small aircraft, such as gliders or ultralights, may not carry any electronic equipment or transponders. Pilots therefore must take the responsibility to see and avoid such traffic.

Threat Detection and Display

TCAS's complex threat-detection algorithms begin by classifying intruders into one of four discrete levels [4]. To project an aircraft's position into the future, the system performs a simple linear extrapolation based on the aircraft's estimated current velocity. The algorithm then uses several key metrics to decide whether an intruder is a threat, including the estimated vertical and slant-range separations between aircraft. Another parameter, called tau, represents the time until the closest point of approach between aircraft.

A display in the cockpit depicts nearby aircraft, indicating their range, bearing, and relative altitude; an arrow indicates whether the intruder is climbing or descending. Such traffic display information aids the pilot when attempting to visually acquire traffic out the windscreen. Distant, non-threatening aircraft appear as hollow diamond icons. Should the intruder close within certain lateral and vertical limits, the icon changes to a solid diamond, alerting the flight crew that traffic is proximate but is not yet a threat.

If a collision is predicted to occur within the next 20 to 48 seconds (depending on altitude), TCAS issues a traffic advisory (TA) in the cockpit. This advisory comes in the form of a spoken message, "traffic, traffic." The traffic icon also changes into a solid yellow circle. The TA alerts the pilot to the potential threat so that the pilot can search visually for the intruder and communicate with ATC about the situation. A TA also serves as a preparatory cue in case maneuvering becomes required. If the situation worsens, a resolution advisory (RA) warning is issued 15 to 35 seconds before collision (again depending on altitude). The RA includes an aural command such as "climb, climb" and a graphical display of the target vertical rate for the aircraft. A pilot receiving an RA should disengage the autopilot and manually control the aircraft to achieve the recommended vertical rate. Figure 3 shows both the traffic and RA displays.

Threat Resolution

Once the criteria for issuing an RA have been met, TCAS's threat-resolution algorithms determine what maneuver is appropriate to avoid a collision. First, the algorithm decides the vertical sense of the maneuver—that is, whether the aircraft needs to climb or to descend. Second, the system figures the strength of the RA—that is, how rapidly the plane needs to change its altitude. TCAS works only in the vertical direction; it does not select turning maneuvers, because bearing accuracy is generally not sufficient to determine whether a turn to the left or right is appropriate.

Figure 4 shows a simplification of the sense-selection process. In general, two maneuver templates are examined: one based on a climb, and one based on a descent. Each template assumes a 5 sec delay before a response begins, followed by a 0.25 g vertical acceleration until reaching a target vertical rate of 1500 ft/min. In the meantime, the intruder aircraft is assumed to continue in a straight line at its current vertical rate. The TCAS algorithm selects the maneuver sense providing the largest separation at the predicted closest point of approach. In the situation shown in Figure 4, TCAS would on the basis of these criteria advise the aircraft to descend.

If the intruder is also TCAS equipped, the sense of the RA is coordinated through the Mode S data link to ensure that both aircraft do not select the same vertical sense. Should both aircraft simultaneously select the same sense—say, both select a climb RA—the aircraft with the lower numerical-valued Mode S address has priority and will continue to display its climb RA. The aircraft with the higher Mode S address will then reverse its sense and display a descend RA.

Once the sense has been selected, the strength of the RA maneuver is determined by using additional maneuver templates (Figure 5). Each template again assumes a 5 sec delay, followed by a 0.25 g acceleration to reach the target vertical rate. TCAS selects the template that

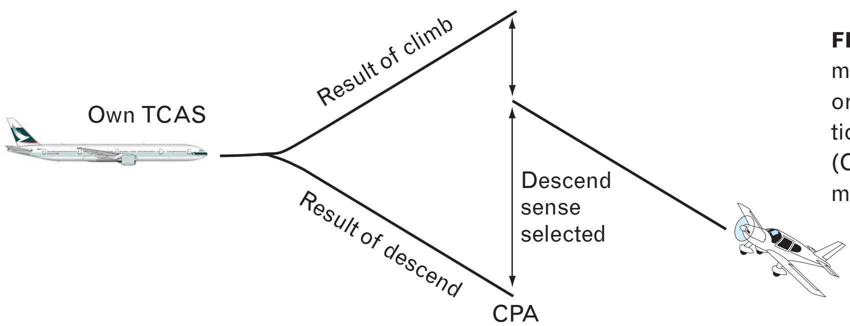

FIGURE 4. The TCAS algorithm selects the maneuver "sense"—that is, whether to climb or descend—that provides the largest separation at the predicted closest point of approach (CPA). In the scenario shown here, the correct maneuver would be to descend.

requires the smallest vertical-rate change that achieves at least a certain minimum separation. In the example shown in Figure 5, the TCAS aircraft is currently descending at a rate of 1000 ft/min when an RA is issued. Five maneuver templates are examined, with each template corresponding to a different target vertical rate. The minimum-strength maneuver that would provide the required vertical separation of at least 400 ft would be to reduce the descent rate to 500 ft/min; the pilot would receive an aural message stating that instruction. Descent rates exceeding 500 ft/min would appear in red on the RA display. Note that in Figure 5 if the intruder were 100 ft higher, then the selected RA would instead be "don't descend." If the intruder were another 100 ft higher still, the selected RA would be "climb."

Due to TCAS's 1 Hz update rate and filtering lags, its estimates may lag the actual situation during periods of sudden acceleration. This lag may in turn lead to an inappropriate RA sense or strength. To help alleviate this problem, TCAS refrains from issuing an RA if there are large uncertainties about the intruder's track. TCAS also includes algorithms that monitor the evolution of the encounter and, if necessary, issue a modified RA. The strength of an RA can be increased—for example, changing from "don't descend" to "climb" (target rate of 1500 ft/min) to "increase climb" (target rate of 2500 ft/min). Under certain conditions, if it becomes clear that the situation is continuing to degrade, TCAS can even reverse the sense of the RA, from climb to descend, or vice versa. Coordination of this reversal with a TCAS-equipped intruder aircraft will also be performed through the Mode S data link. Sense reversal is especially challenging because only a few seconds may remain before collision. Any latencies involved in pilot and aircraft response could result in an out-of-phase response that further reduces separation.

Performance Assessment

The main functions of TCAS are to identify a potential collision threat, communicate the detected threat to the pilot, and assist in the resolution of the threat by recommending an avoidance maneuver. As an alerting

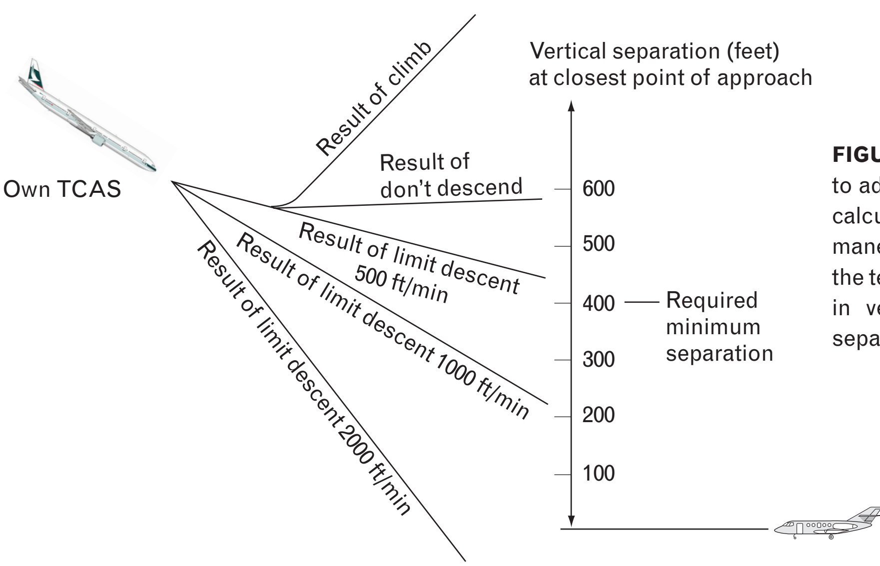

FIGURE 5. Once TCAS determines whether to advise an aircraft to climb or to descend, it calculates the speed at which the plane must maneuver to avoid collision. TCAS selects the template that requires the smallest change in vertical rate that achieves the required separation.

system, TCAS operates quietly in the background most of the time. When the algorithms determine that action is needed, TCAS interrupts the flight crew to bring the threat to their attention. This interruption may be vitally important if the pilots are not aware of the threat. In some situations, however, aircraft may operate safely close together; in those cases, the TCAS alerts are more of a nuisance than a help. An example is during an approach to closely spaced parallel runways. In good visibility conditions, pilots can be given the authority to maintain separation from parallel traffic by monitoring nearby aircraft visually through the windscreen. TCAS, however, does not know that visual separation is being used and may issue a TA or an RA, thus introducing a distraction on the flight deck when pilots should be especially focused on performing their approach procedures. TCAS does inhibit issuing RAs when an aircraft is less than 1000 ft above the ground, both to reduce nuisances at low altitude and to help ensure that any TCAS advisories do not conflict with potential terrain hazards.

TCAS operates in a complex, dynamic environment. Each decision maker (Air Traffic Control, pilots, TCAS itself) uses different information sources and operates under different constraints and with different goals. TCAS may have more accurate range or altitude information about an intruder than flight crews or ATC do. But TCAS cannot observe all the factors affecting a traffic encounter, such as the location of hazardous weather, terrain, aircraft without transponders, or ATC instructions—a major reason that TCAS is certified to operate only as an advisory system. Pilots are ultimately responsible for deciding on the correct course of action, weighing TCAS alerts with the other information available to them.

TCAS is extremely successful in providing a last-resort safety net, and does not necessarily need to operate perfectly to be effective. Still, it is important to identify situations where TCAS may have difficulty—and, if possible, modify the logic to better handle such circumstances.

Lessons from a Disaster

On the night of 1 July 2002, a Boeing B-757 operated by the cargo carrier DHL collided with a Russian Tu-154 passenger jet at 34,940 ft over the small town of Überlingen, Germany (Figure 6). The accident destroyed both aircraft and killed all 71 crew members and passengers aboard the two planes. What was especially troubling about this accident is that both aircraft were equipped with TCAS.

As with most aviation accidents, a string of events occurred leading up to the collision. First, the nominal separation standards between aircraft were lost through a combination of problems and errors at the air traffic control facility monitoring the aircraft. As a result, the two aircraft were on a collision course much closer together than is normal while cruising at 36,000 ft.

Figure 7 schematically summarizes the event. Forty-three seconds before the collision, ATC instructed the Russian aircraft to descend because of the traffic conflict. Before the controller finished his verbal instruction, however, TCAS on the Russian aircraft issued an RA advising the pilot to climb. A coordinated descend

FIGURE 6. A mid-air collision over Überlingen, Germany, in 2002 killed 71 people—even though both planes were equipped with TCAS. (Photograph source: German accident investigation report.)

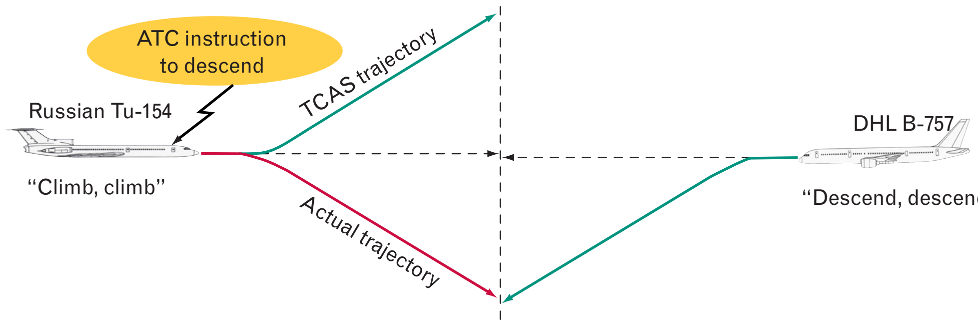

FIGURE 7. The Überlingen mid-air collision occurred after the Russian pilot decided to heed the air traffic control instruction to descend rather than the TCAS advisory to climb.

RA was issued on the DHL aircraft at the same time. The DHL pilots followed their RA and began to descend; the Russian flight crew followed the ATC instruction and also descended. Shortly thereafter the RAs on each aircraft were strengthened to "increase climb" on the Russian aircraft and "increase descent" on the DHL aircraft. About 35 seconds after the TCAS RAs were issued, the aircraft collided.

One of the immediate causes for the accident, as described in the German accident report, was the fact that the Russian flight crew chose to follow the ATC clearance to descend rather than follow the TCAS RA to climb [5]. The Russians' choice to maneuver opposite to the RA defeated the coordination logic in TCAS. An advisory system like TCAS cannot prevent an accident if the pilots don't follow the system's advice. The DHL crew, however, did follow the TCAS RA and yet they still collided. The question thus arises: why didn't TCAS reverse the sense of the RAs when the situation continued to degrade? Had it done so, the Russian aircraft would have received a descend RA, which presumably it would have followed, since the crew had already decided to descend in response to the ATC clearance. The DHL aircraft would have received a climb RA, which it likewise would have presumably followed, since its crew had obeyed the original RA. This is not to say that a reversal is always a good idea, however. In many encounters, a reversal would reduce separation and increase the risk of a collision. Because of sensor limitations and filtering lags, it turns out to be quite difficult to trigger reversals when they are needed while avoiding them when they are not needed.

A closer examination of the reversal logic revealed several areas in which earlier design assumptions proved inadequate in situations when one aircraft maneuvers opposite to its RA. In order for an RA reversal to be issued, the Version 7 threat logic requires four basic conditions to be satisfied; these conditions are illustrated in Figure 8. First, a reversal will be triggered only by the aircraft with priority—that is, the aircraft with the lower Mode S address. If the aircraft has a higher Mode S address than the intruder, the RA sense will be reversed only when directed to do so by the priority aircraft through the data link. Second, the maneuver templates projecting the situation into the future need to predict that insufficient separation between aircraft will occur unless a sense reversal is issued. Third, a maneuver template projecting the response to a reversed-sense RA needs to predict adequate separation between aircraft. Fourth, the two aircraft in danger of colliding must be separated by at least 100 ft vertically. (This last condition is intended to prevent reversals from occurring just as aircraft cross in altitude.)

A closer look at the Überlingen accident, as shown in Figure 9, reveals why TCAS did not issue an RA reversal. Responsibility for triggering the reversal rested with the Russian aircraft, which had a lower Mode S address. The Russian aircraft was operating under an active climb RA. The climb-RA maneuver template predicted adequate separation between aircraft, at least until the final few seconds; therefore, TCAS did not issue an RA reversal. Since the Russian aircraft was not actually following the climb maneuver, of course, the template's predictions were invalid.

What is startling, however, is that even if the DHL aircraft had the lower Mode S address (and therefore priority), the planes still probably would have collided. In the hypothetical case in which the DHL aircraft had priority, three of the four conditions required to trigger a reversal, as shown in Figure 8, would have held:

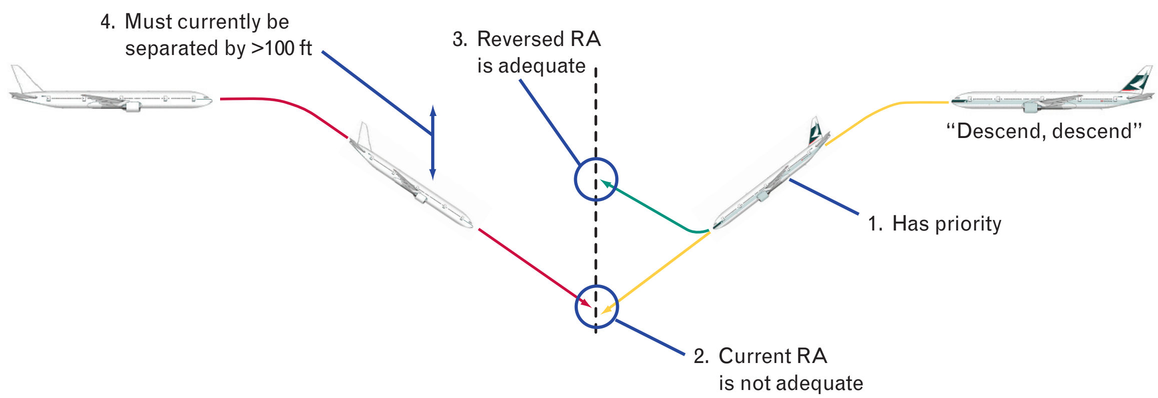

FIGURE 8. In order for TCAS to reverse its maneuver instruction—e.g., from "descend" to "climb"—four conditions must hold. (1) The reversal can be triggered only by the aircraft with priority. (2) The maneuver template must predict that insufficient separation between aircraft will occur if the present RA is followed. (3) A maneuver template must predict that a reversed RA will result in adequate separation between aircraft. (4) The two aircraft in danger of colliding must be separated by at least 100 ft vertically.

the DHL aircraft would have had priority; the DHL aircraft's descend RA would have shown that a collision was still predicted; and the projection of a reversal-climb RA would have predicted adequate separation. However, both aircraft remained within 100 ft vertically of each other throughout the encounter, and so this fourth criterion for permitting a reversal still would not have been met.

To reduce the risk of this type of collision, researchers funded by the European Organization for the Safety of Air Navigation, or Eurocontrol, have proposed a change to the TCAS threat logic. Eurocontrol's proposal aims to improve reversal performance in encounters in which both aircraft become involved in a so-called vertical chase, as occurred at Überlingen. The proposal includes two major components. First, when using maneuver templates, TCAS would no longer assume that the TCAS aircraft would follow its RA. Instead, TCAS would check the recent vertical motion of the aircraft; if this motion is not compatible with the RA that had been issued, then TCAS would revert to models using the aircraft's current vertical rate instead of its predicted motion in response to the RA. Second, the proposal would eliminate the 100 ft separation requirement, allowing TCAS to reverse sense in vertical-chase situations. The combination of these changes would have produced RA reversals in the Überlingen accident—no matter which aircraft had priority. Starting in 2004, the FAA funded Lincoln Laboratory to answer two fundamental questions: how often do RA reversal problems occur in U.S. airspace, and how effective would the European change proposal be?

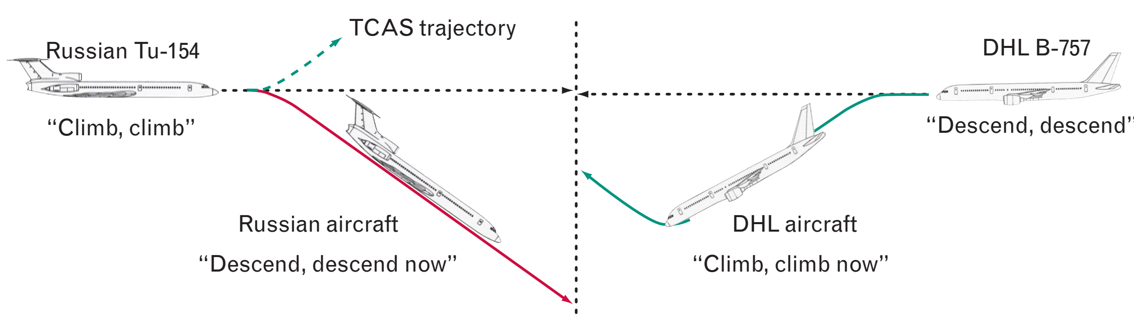

FIGURE 9. The Überlingen accident might have been averted if TCAS had issued an RA reversal as shown. Responsibility for triggering the reversal rested with the Russian aircraft, which had priority and which was operating under a "climb" RA. But until the final few seconds, the climb RA maneuver template predicted adequate separation between aircraft; therefore, TCAS did not issue an RA reversal. Since the Russian aircraft was not actually following the climb maneuver, but rather the air traffic control instruction to descend, the template's predictions were tragically invalid.

TCAS Monitoring

Following the Überlingen accident, researchers set about monitoring the European airspace to estimate how common this type of situation was. A total of ten events, including the Überlingen accident, were positively identified in which one aircraft flew opposite to its RA, a reversal did not occur, and either a collision or near miss occurred. Eurocontrol estimated on the basis of the number of flight hours examined that these types of situations occur more than fifty times per year in European skies, and that a mid-air collision in Europe due to this problem might be expected once every four years.

In recent years, several countries—the United States, Britain, France, Germany, and Japan—have been monitoring TCAS to find out if the system's advisories are appropriate and to understand the impact that these TCAS advisories have on airspace operation. All U.S. monitoring/analysis has been performed at Lincoln Laboratory, using an FAA production Mode S sensor located in Lexington, Massachusetts. Following the Überlingen accident, the FAA tasked Lincoln Laboratory to begin monitoring for occurrences of the type of situation described above. To accomplish this, we pass sensor data through a series of software tools (Figure 10) to examine the details of TCAS events occurring in the Boston area airspace.

Procedures for transmitting TCAS RA information to Mode S ground sensors are a part of the basic Mode S and TCAS designs. Whenever TCAS issues an RA to an aircraft within the coverage area of a Mode S sensor, the aircraft's transponder automatically informs this ground sensor that information is available for read-out. On each radar sweep over the duration of the RA, the sensor requests the aircraft's RA Report. This report contains the Mode S address of the TCAS aircraft, the type of RA, and (for TCAS Version 7) an identification of the intruder triggering the RA.

Correlation of RA Reports with the TCAS aircraft surveillance data is performed via the aircraft's unique Mode S address, which is present in both the RA reports and the aircraft surveillance data, as well as via time stamps, which are applied by the sensor and show the time of receipt for all communication and surveillance data. All data—communication and surveillance—are recorded for later playback and analysis.

As shown in Figure 10, Lincoln Laboratory performs four types of processing: statistics; pilot response (compliance with RAs); filtering for specific events; and playback. We discuss the first three types in the following sections. The fourth, the playback feature, allows detailed review of the TCAS logic performance. The 5 sec radar surveillance position reports are converted to 1 sec inputs for TCAS. The data can then be played through one of several different versions of the TCAS

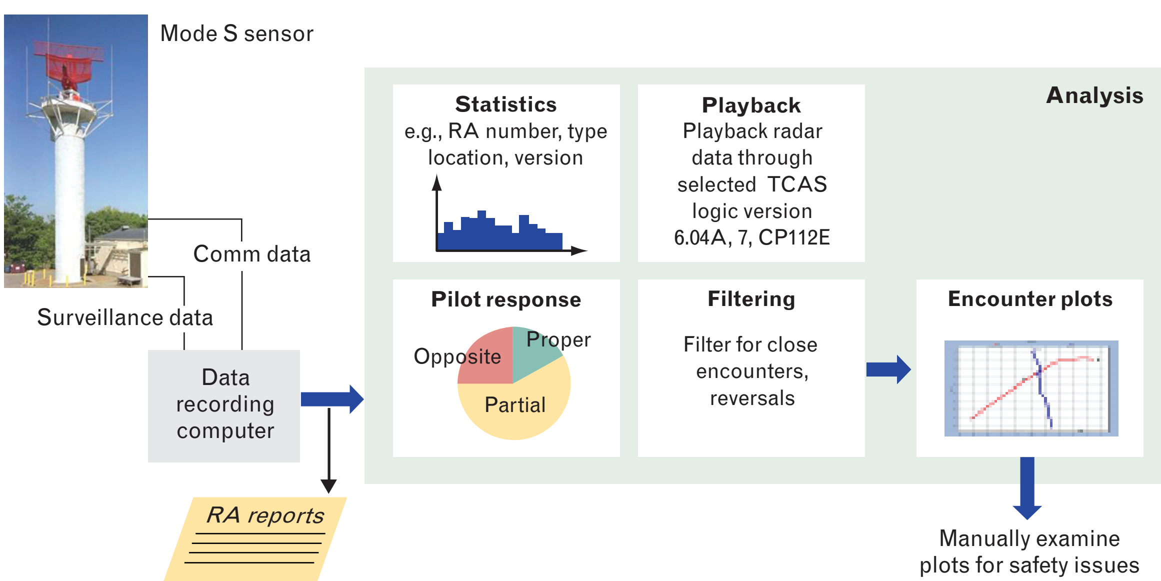

FIGURE 10. A Lincoln Laboratory facility monitors TCAS operations in the United States to find out if the system's advisories are appropriate and to understand the impact that these TCAS advisories have on airspace operation.

logic, allowing comparison of the performance of different TCAS versions, or examination of the effect of a proposed logic change. The playback can be stepped through the encounter in 1 sec increments and allows viewing of key TCAS logic parameters at each step.

Figure 11 shows the location of RAs as recorded by the Lincoln Laboratory monitoring program from June 2005 through January 2006. Over this time period, monitoring took place for approximately 190 days, and roughly 200,000 Mode S flight hours were observed within the sensor's 60-nautical-mile coverage area. We observed a total of 1725 RA events, corresponding to an average of 9 RAs per day, or about one RA every 116 flight hours.

This RA rate is typically an order of magnitude larger than that in European terminal airspace. The higher RA rate in Boston is thought to be due, at least in part, to U.S. air traffic control use of visual-separation procedures when visual meteorological conditions (VMC) prevail, increasing the number of encounters in which aircraft pass each other safely even though they are within TCAS RA thresholds. In particular, Figure 11 shows a number of RAs along the parallel approaches to runways 4L and 4R at Boston's Logan Airport. In VMC, aircraft may be vectored onto final approaches to these two runways as the pilots accept responsibility of maintaining safe separation from the parallel traffic. In some cases, TCAS may still alert because of the close proximity of aircraft. Many of the RAs elsewhere in the airspace are due to the large density of small general-aviation aircraft in the United States that may operate more closely to other air traffic in VMC than is typical in Europe.

When air traffic control allows use of visual-separation procedures, pilots may ignore an RA, or move contrary to the RA, because the intruder aircraft is in sight. Pilot non-compliance to an RA may not necessarily compromise safety in a particular encounter. It can, however, lead to a degrading situation in which a reversal will not occur when necessary, such as at Überlingen. Examination of pilot response is therefore a key component of the Lincoln Laboratory monitoring.

As an example, Figure 12 shows pilot response to climb RAs during the eight-month period from June 2005 through January 2006. For a climb RA, TCAS expects the pilot to begin to maneuver within 5 sec and to achieve a 1500 ft/min vertical rate. If the aircraft is already climbing faster than 1500 ft/min, the RA is instead "maintain climb," and the pilot is expected to continue at the current rate. The delay in pilot response was estimated as the time required for the vertical rate to change by at least 400 ft/min.

Examination of the data shown in Figure 12 indicates that only 13% of pilot responses met the assumption used by TCAS: pilot responses within 5 seconds and achieving a 1500 ft/min vertical rate. In 63% of the cases, the pilots maneuvered in the proper direction but were not as aggressive or prompt as TCAS assumed. Pilots maneuvered in the opposite direction to the RA in 24% of the cases. Some of these opposite responses are believed to be due to visual acquisition of the intruder aircraft and the pilot's decision that following the RA was not necessary. Although such a decision may

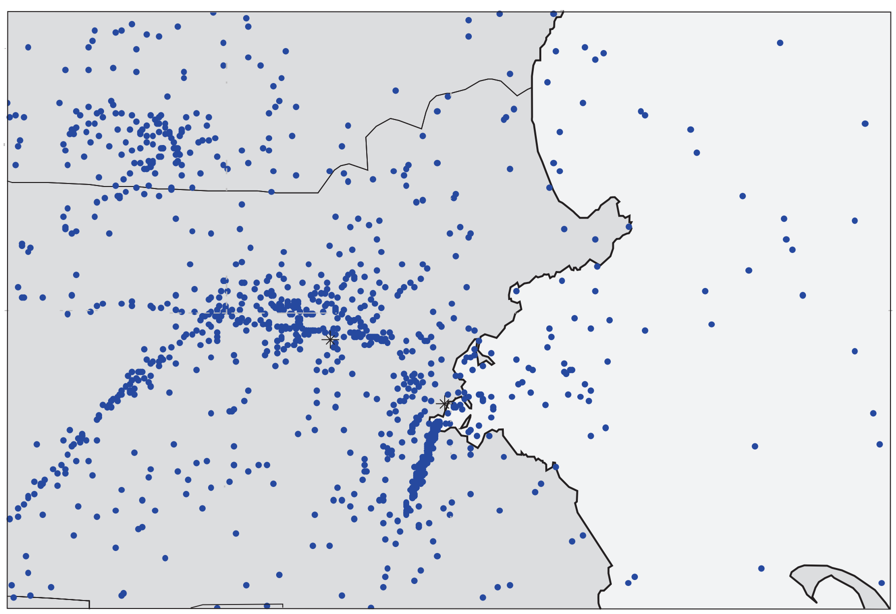

FIGURE 11. The location of RA events as recorded by the Lincoln Laboratory monitoring program for the time period June 2005 through January 2006. Over this time period, monitoring took place for approximately 190 days, and roughly 200,000 Mode S flight hours were observed within the sensor's 60 nmi coverage area. We observed a total of 1725 RA events, corresponding to an average of 9 RAs per day, or approximately one RA every 116 flight hours.

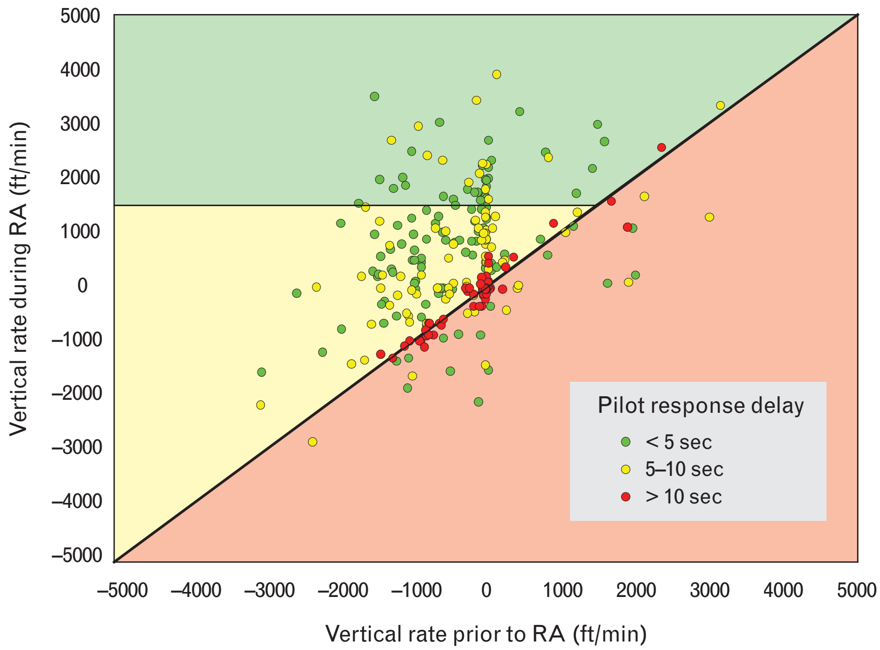

FIGURE 12. Pilot compliance with climb RAs. Each circle corresponds to one RA event for a TCAS aircraft. The green-shaded region indicates responses that achieved the intended vertical rate; the yellow segment indicates responses that were in the correct direction but did not achieve the intended vertical rate; the red shading indicates responses that were in the wrong direction.

be reasonable in certain cases, the fact remains that maneuvering opposite to the TCAS RA invites exactly the kind of vertical chase that happened at Überlingen. The European change proposal would provide an additional safety net should such a vertical chase occur and aircraft continue to move on a collision course.

Detecting Reversal Problems

A key part of Lincoln Laboratory monitoring efforts since mid-2004 has been to find instances of RA reversal problems in the Boston airspace. Automated tools extract encounters in which a TCAS RA occurs and separation between aircraft is small. These encounters are then examined to find those in which the two aircraft moved in the same vertical direction after the start of the RA event.

The Lincoln Laboratory monitoring program detected two RA reversal problem events. Figure 13 diagrams one of these encounters, in which a TCAS-equipped aircraft came within 0.3 nmi horizontally and 100 ft vertically of another aircraft that did not have TCAS. As the aircraft neared each other, TCAS issued a descend RA, which the pilot followed. At about the same time, however, the non-TCAS aircraft also began a descent, presumably on the basis of visual identification of the TCAS aircraft and an attempt to avoid a collision. TCAS then issued an "increase descent" RA, which the pilot again followed. At the same time, the non-TCAS aircraft also increased its descent rate. TCAS maintained the descend sense even after the non-TCAS aircraft had dropped below the TCAS aircraft. TCAS did eventually issue a reversal, instructing the aircraft to climb. However, this reversal occurred essentially as the two aircraft passed each other and was too late to be of benefit. This encounter, which took place in April 2005, is of the same general type as that in the Überlingen accident in that an RA reversal should have been issued earlier. The findings of the Lincoln monitoring program indicate that RA reversal problems occur in U.S. airspace at a rate comparable to that in Europe.

Assessing Safety

Safety analysis of TCAS is based in part on a comprehensive, statistically valid set of data describing TCAS performance across a wide range of encounter situations. Specific problem situations also need to be identified

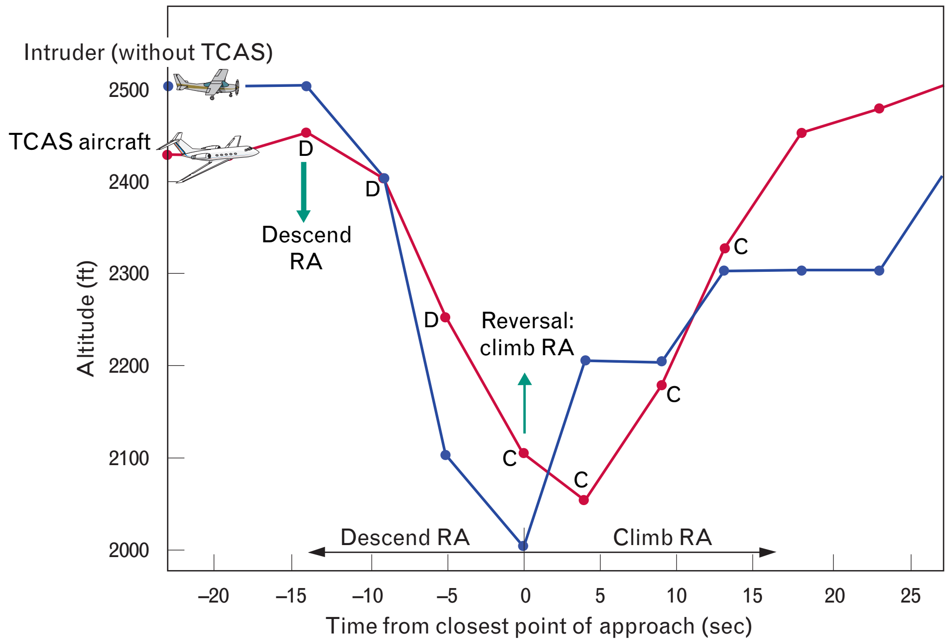

FIGURE 13. In this encounter, a TCAS-equipped aircraft came within 0.3 nmi horizontally and 100 ft vertically of another aircraft that did not have TCAS. The RA reversal came too late.

and judged as to their criticality and likelihood. Extensive flight testing is required to support modeling sensor performance, automation, human interaction with TCAS advisories, and flight characteristics. However, flight tests alone cannot provide enough data to make a complete system assessment. Thus a combination of modeling based on flight experience and fast-time simulation of many encounters is needed.

A key performance metric is the reduction in collision risk achieved by equipping with TCAS. This risk is expressed in terms of Near Mid-Air Collision (NMAC) events, defined to occur when separation between two aircraft is less than 100 ft vertically and 500 ft horizontally. The probability of Near Mid-Air Collision is P(NMAC). The ratio of P(NMAC) when TCAS is used to P(NMAC) without TCAS is commonly referred to as the risk ratio. Changes in TCAS algorithms, such as those included in the European change proposal, can be evaluated by examining their effect on risk ratio.

Assessment of safety requires more than simply the application of a single analytical model. Several tools must be brought to bear, each focusing on a different aspect of the overall system. In particular, the collision risk problem can be partitioned into two regimes: an outer loop that encompasses system failures and events that lead up to a critical close-encounter event, and an inner loop that covers the second-by-second details of an encounter in a dynamic analysis, given the conditions that were defined in the outer-loop regime (Figure 14).

A fault tree is typically used to model the outer-loop system failures or events that in turn define the environment for a fast-time inner-loop simulation of a close encounter. For example, the probability that a transponder will fail to provide altitude information can be estimated in the fault tree, and P(NMAC) for that type of encounter can be computed in a detailed fast-time simulation. Results are then combined in the fault tree with corresponding performance data and probabilities for other conditions, leading to a global estimate of system safety. Researchers can perform sensitivity studies by modifying event probabilities in the fault tree and observe their impact on overall risk, without requiring new fast-time simulations.

The outer-loop regime defines what conditions apply to the set of close encounters that are dynamically simulated in the inner loop. Outer-loop conditions include airspace environment (e.g., low altitude, high altitude, U.S. airspace, European airspace); encounter characteristics (e.g., speeds, geometry of encounter), intruder aircraft equipage (e.g., transponder-equipped, TCAS-equipped); system component failures; pilot response to TCAS RAs (e.g., failure to respond, normal response);

environmental conditions; and finally, ATC involvement in resolving the close encounter.

The outer-loop modeling requires a valid model of the types of close encounters that may occur. This so-called encounter model specifies a number of variables that are selected randomly in every fast-time simulation run. Key variables include the geometry of the encounter, aircraft speeds, and vertical accelerations. The encounter modeling process begins by collecting thousands of hours of air traffic radar data and using a set of filters to extract from these data any close encounters between aircraft. The characteristics of each close encounter are then compiled into a statistical distribution describing the likelihoods that various conditions are present. When generating encounter scenarios, separate software randomly selects parameter values from these distributions, computes the initial conditions for the simulation, and stores the results in an input file.

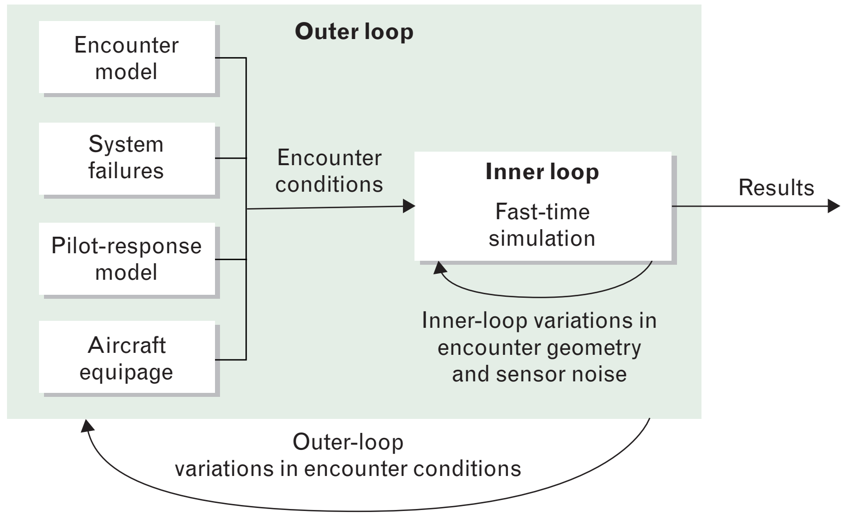

FIGURE 14. The aircraft mid-air collision risk problem has two parts: an outer loop that encompasses system failures and events that lead up to a close encounter, and an inner loop that covers the second-by-second details of an encounter in a dynamic analysis.

The inner-loop dynamic simulation takes the status of system components and the environment and computes P(NMAC) over a representative range of encounter situations. Each encounter scenario is executed once without TCAS and once with TCAS. Additional runs may be performed to compare the performance of different TCAS algorithms. These runs, using identical initial conditions, facilitate making direct estimates of the safety provided by TCAS.

Lincoln Laboratory's Safety Assessment Tool

Lincoln Laboratory recently designed and implemented (using The MathWorks MATLAB, Simulink, and Real Time Workshop software packages) a fast-time Monte Carlo simulation capability called the Collision Avoidance System Safety Assessment Tool. This system takes encounter model data as an input and simulates three-dimensional aircraft motion. The simulation includes several integrated sub-models, as shown in Figure 15. These sub-models include TCAS logic, a visual-acquisition model, a pilot-response model, and a vehicle dynamics model. A sensor noise model is also included. A performance analysis module examines the aircraft trajectories to determine miss distances and to compute P(NMAC). To reduce computation time, batch simulation runs are performed with Lincoln Laboratory's LLGrid parallel computing facility [6]. LLGrid enables simulation of one million encounter situations in approximately 3.5 hours, allowing enough flexibility to interactively investigate changes to TCAS or other collision avoidance systems.

The simulation includes flight-certified TCAS code obtained from a TCAS vendor. The logic in the simulation is thus identical to that in actual aircraft, providing high fidelity and an ability to replicate the full range of logic behavior. Information from the TCAS logic is passed to a pilot-response model (to respond to RAs), to a visual-acquisition model (triggering improved pilot visual-search efficiency) and to the other aircraft's TCAS unit (if equipped) to handle maneuver coordination.

A visual-acquisition model estimates the probability that a pilot will see the other aircraft through the windscreen. This model relies on a technique developed for accident investigations, safety analyses, and regulatory processes [7]. The model's basis is that visual acquisition is limited by target search time over a given volume of space. In the model, the probability of visually acquiring a threat during one time step is given by

$$\lambda = \beta \frac{A}{r^2} ,$$

where β is a constant, A is the visual area presented by the target, and r is the range to the target. If the aircraft are on a collision course, r decreases with time, so the acquisition probability increases smoothly until the point of closest approach. The value of A may vary as an aircraft changes orientation. The value of β depends on visibility, contrast, the number of pilots searching, and whether those pilots have been cued by an ATC or TCAS traffic advisory. Values for β have been validated in flight experiments. The visual-acquisition model estimates the probability of a pilot visually detecting another aircraft by a certain time and thus helps identify encounters that might be avoided by visual acquisition.

Aircraft motion normally follows a scripted set of maneuvers as specified by the encounter model. These maneuvers can include vertical or lateral acceleration such as a level-off or turn, plus changes in airspeed. If a TCAS RA is issued, the motion transitions to a new set of control behaviors as defined by a pilot-response model. We use different models to explore a variety of possible pilot behaviors, including pilots who respond exactly as TCAS assumes as well as pilots who respond slowly, move more aggressively than expected, maneuver in the opposite direction as the RA calls for, or make no maneuver at all.

European Change—For the Better?

Between 2004 and 2006, the FAA and Eurocontrol conducted an international study to assess the performance of the European change proposal [8]. Figure 16 shows data from Lincoln Laboratory simulations, as part of this study, that demonstrate how the European change proposal would affect the measured vertical miss distance between aircraft in encounters similar to Überlingen—that is, when both aircraft are equipped with TCAS but when one aircraft does not follow its RA.

Clearly, the European proposal would in a vast majority of cases affected by the proposal—92%—result in an increase in vertical separation. A full 22% of the affected cases are considered saves; that is, a near mid-air collision would have occurred with the current version of TCAS but would not occur if the proposed change were to be implemented. In only 2% of the affected cases would the situation be reversed, with the proposed change resulting in a near miss, while the current TCAS would not.

Lincoln Laboratory simulations were also run with an encounter model representing European airspace. In encounters involving two TCAS-equipped aircraft in which both pilots respond appropriately to their RAs, TCAS provides a risk ratio of approximately 0.02. That is, if pilots obey the RA, the use of TCAS reduces the risk of mid-air collision by about a factor of 50. If instead one pilot does not respond to the RA, the risk ratio rises by an order of magnitude, to 0.23.

Figure 17 summarizes the overall impact of TCAS according to the estimated number of years between mid-air collisions over Europe. These estimates, which were based on the Lincoln Laboratory simulation studies, consider two factors: the likelihood with which pilots follow their RAs, and the type of TCAS logic being used. With no TCAS at all, one mid-air collision

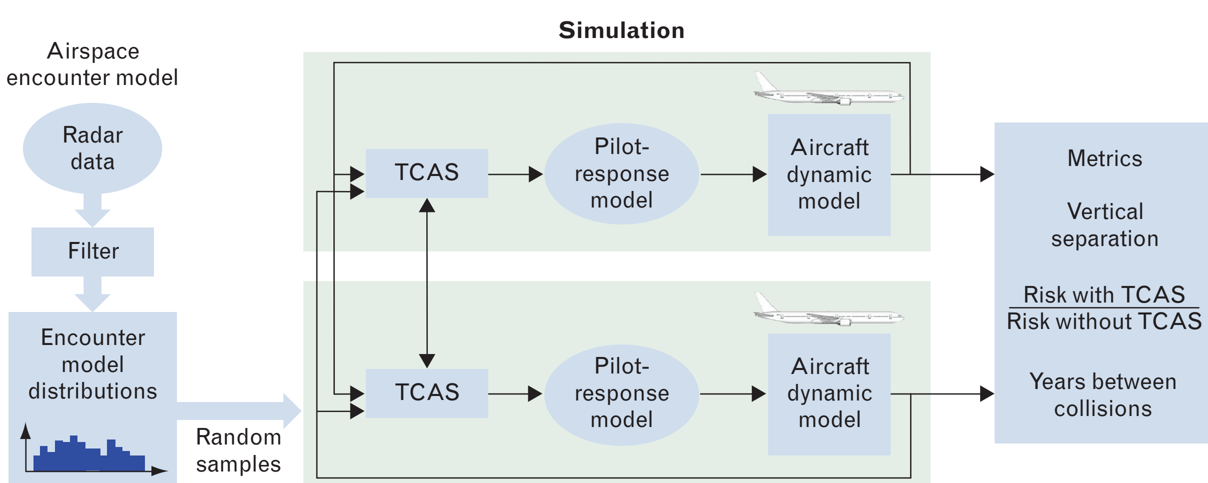

FIGURE 15. A set of software modules implemented at Lincoln Laboratory simulates three-dimensional aircraft motion based on data from encounter models. The fast-time simulator runs on the LLGrid parallel computing facility.

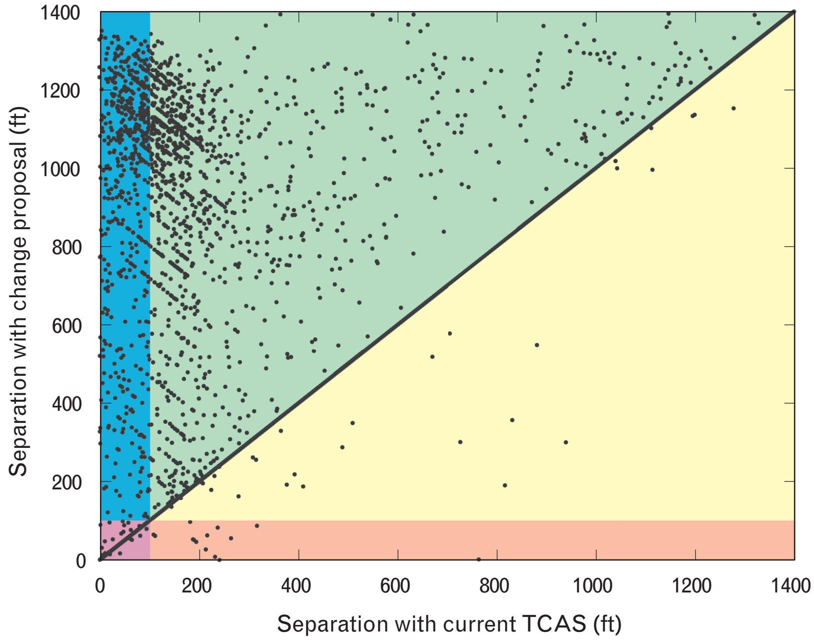

FIGURE 16. Each data point represents one encounter that was simulated twice: once with the existing TCAS logic and once assuming adoption of the European change proposal. Encounters in which the proposed change does not affect the vertical miss distance lie on the diagonal line. Points above the line represent encounters where the proposed change would increase separation; points below the line indicate encounters where the change would reduce separation.

could be expected over Europe approximately every three years. With deployment of TCAS Version 7 (blue curve), the years between collisions depend heavily on how often crews conform to RAs. Safety increases sharply as more pilots follow their RAs. Introducing the European change proposal should improve safety even further (green curve). Clearly, aviation safety can be best enhanced through a combination of measures: upgrading the TCAS algorithms while also improving pilot training and procedures to increase RA conformance. The FAA is considering the economic and safety trade-offs involved in mandating an upgrade to all TCAS units worldwide. Because of this analysis, it is possible that within the next year the FAA will issue directives requiring aircraft operators to implement new algorithms incorporating the European change proposal.

Better Sensing and Algorithms

As the European change proposal illustrates, improvements are still possible and being investigated—as are completely new technologies for collision avoidance. A key issue is how to best apply sensors, displays, automation, procedures, and controls to enable operating a complex collision avoidance system at a desired level of performance even as the types of aircraft and procedures for air traffic management change.

Triggering an alert requires the automation to determine on the basis of its internal models that intervention is required. This decision may conflict with the human operator's mental model. Such tension is good when the human needs to be alerted to a problem that requires attention, but can be undesirable if the human has access to information that disagrees with the need for an alert or for action. Along these lines, areas of potential improvement in collision avoidance system design include enhanced surveillance information and more sophisticated modeling and decision-making algorithms.

TCAS can be only as good as the data that it works from—particularly the estimates of an intruder aircraft's position, velocity, and acceleration. Because position measurements are updated only once a second, rapid changes in aircraft trajectory cannot be detected or tracked immediately. Acceleration information obtained directly from the flight management system on the TCAS aircraft could

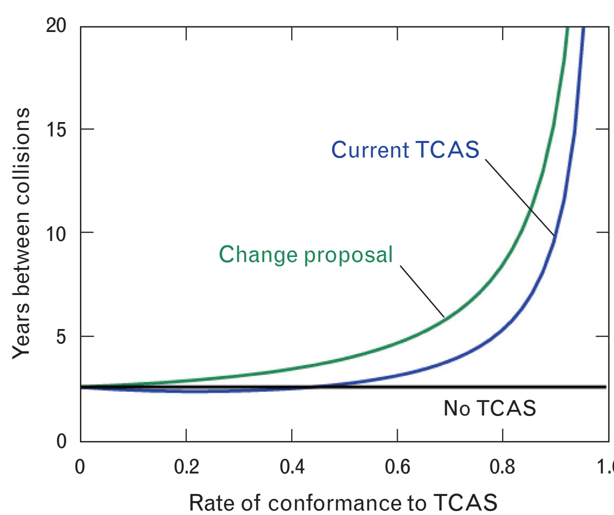

FIGURE 17. For a given rate of pilot conformance to TCAS instruction, the risk of collision would be lower under the proposed European change than with the current system.

be used to provide lead information to the dynamic models that TCAS uses to determine whether an alert is needed or whether an RA is being followed. Access to additional intent information from the intruder aircraft, such as the altitude at which it intends to level off, would also greatly improve TCAS's ability to determine what type of RA should be issued, or if one should be issued at all.

Improvements are also possible for the trajectory model templates on which TCAS bases its predictions. TCAS uses a two-stage decision-making process. First, the system projects current traffic into the future on the assumption that both aircraft continue in straight lines with no acceleration. The rationale behind using this nominal template is that alerts are issued only when they are necessary to avoid a collision. The accuracy of trajectory prediction generally degrades into the future, so some cutoff or maximum look-ahead time is typically required to avoid nuisance alerts. That uncertainty precludes TCAS from making accurate collision avoidance decisions more than 30 to 40 seconds into the future.

If the first-stage modeling predicts insufficient separation between aircraft, TCAS then selects one of several avoidance templates and instructs the pilot to make this recommended maneuver. The safety of the two-stage system is ensured by tuning the alerting parameters so that, on balance, first-stage alerts are issued early enough that ample avoidance trajectories remain. Encounter models and Monte Carlo simulations are integral to this evaluation and tuning process.

A single integrated decision-making stage could further improve performance. A system that simultaneously examined the nominal and avoidance templates would issue alerts only when they were necessary and likely to be successful. Alert timing could then be tightened to ensure that alerts would be issued only when both templates showed that it was appropriate to do so.

TCAS for Unmanned Aircraft

The increasing demand for unmanned aerial vehicles (UAV) adds a new wrinkle to the task of collision avoidance. UAVs are being developed to serve a variety of roles, including border patrol, sea-lane monitoring, vehicle tracking, environmental observation, cargo delivery, and military surveillance. Many of these missions require UAVs to coexist with civilian aircraft. Like piloted aircraft, UAVs are required to see and avoid other air traffic.

TCAS was not designed to be a sole means for the see-and-avoid directive, nor was it originally intended for use on UAVs. TCAS presumes the existence of conventional separation processes, including air traffic control and visual separation, and the surveillance, display, and algorithm designs of TCAS were developed and validated for aircraft with onboard pilots. Four issues in particular are of special concern. First, TCAS can detect only transponder-equipped aircraft, which means that UAVs would be blind to small aircraft such as gliders, hot-air balloons, or ultralights they might encounter. Second, maneuvering is not permitted on the basis of the TCAS traffic display or TAs because of limited bearing accuracy and vertical rate information. Third, remote-control latencies in reacting to RAs may result in maneuvers that induce collisions. Finally, it may be difficult for a UAV's pilot to detect anomalous situations such as altitude-reporting errors or intruders that are maneuvering in a manner incompatible with the RA.

Initial studies by Lincoln Laboratory have provided estimates on how command and control latency affects TCAS performance on a particular UAV, the U.S. Air Force's RQ-4A Global Hawk [9, 10]. Figure 18 shows how risk ratio increases with increasing latency when a pilot is responding to a TCAS RA on Global Hawk. Data are shown for five altitude bands representing different mixes of aircraft and encounter characteristics. To arrive at these results, we adjusted the encounter models to account for the unique flight characteristics of Global Hawk, but no system failures were considered. Nor did we consider issues related to the inability of Global Hawk to visually acquire threats. As Figure 18 shows, risk ratios increase sharply if latencies exceed 10 to 15 sec, especially at low altitudes. Performance at lower altitudes is a serious concern because that is where TCAS may be needed the most: there is a higher potential for encountering aircraft not being managed by ATC. Large latencies reduce TCAS performance to the point where it adds no value. And if latencies grow too large, TCAS may actually induce more risk than exists without TCAS. In some cases, delayed RA reversals can be generated that are out of phase with aircraft motion, potentially causing a collision.

We are pursuing further study into the performance of TCAS on UAVs to address these concerns. We are also investigating the potential for autonomous response to RAs, which might significantly improve safety. Another important factor is the potential for additional sensor

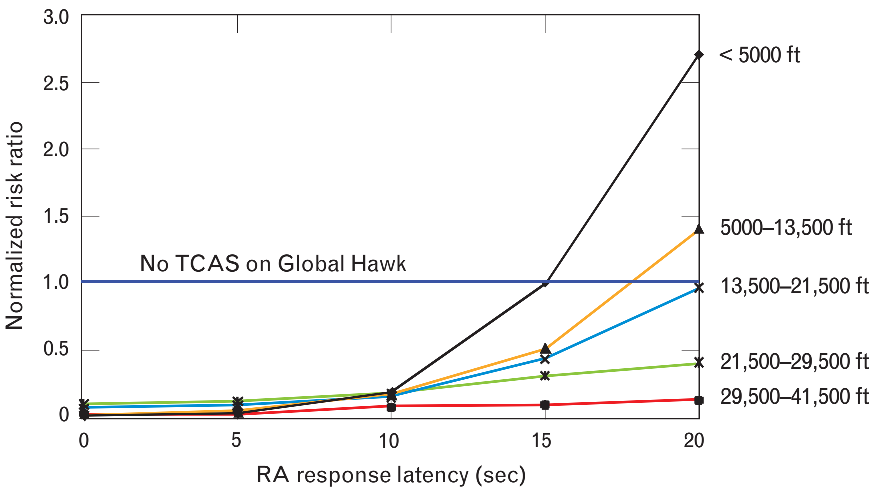

FIGURE 18. Impact of response latency on TCAS performance in an unmanned aerial vehicle (UAV) called Global Hawk. As response latency increases, so does a value called risk ratio, which is defined as the probability of a collision with TCAS divided by the probability of a collision without TCAS. The higher the risk ratio, the less effective is TCAS.

technologies to aid in detecting and avoiding air traffic that is not transponder equipped. Systems based on electro-optical sensors or radar may fill this role, though how these systems and their collision avoidance algorithms interact in the existing air traffic environment needs to be investigated. Such study would require the development of new encounter models for aircraft that do not have transponders as well as environmental models needed to evaluate electro-optical sensor performance across a range of conditions.

Future Challenges

TCAS represents a clear success story in aviation safety. Its successful design was achieved through detailed consideration of sensor characteristics and the coupled dynamic interactions among pilots, air traffic controllers, and aircraft. The result is a fine balance that provides sufficient time to take action and that minimizes alert rates. As the Überlingen accident shows, however, safety cannot be taken for granted, and areas of improvement will always exist in systems that rely on integrating humans and automation for information processing and decision making.

The future still holds several vital issues to be overcome. Remotely piloted or autonomous unmanned aircraft introduce a novel element into an already complex environment. Although the high degree of confidence in today's aviation system has been built on a foundation of more than a hundred years of experience with manned aircraft, such a foundation does not yet exist for unmanned aircraft. The prospect of an aircraft autonomously maneuvering to avoid a passenger jet carrying hundreds of people requires intense scrutiny. Collision avoidance systems will be a focal point of this concern.

At the same time, new technologies are arriving that promise to improve the ease with which collisions can be detected and avoided. These technologies make use not only of enhanced data link capabilities to provide information on the intentions of an intruding aircraft, but also additional modalities such as visual, infrared, or radar sensors. The optical environment, including lighting, haze, clouds, and background clutter, represents aspects that did not need to be considered with radio-frequency-based TCAS but that are now critically important. Fusing TCAS information with these other surveillance sources represents an opportunity and a challenge. Extensive flight testing, modeling, and simulation need to be conducted to fully explore design issues with these new technologies.

The real challenge lies in integrating new collision avoidance technologies with the existing systems and procedures. The Überlingen accident demonstrated the catastrophic outcome that can result from dissonance between two different decision makers in a time-critical situation: namely, an air traffic controller's decision to request a descent and TCAS's Resolution Advisory to climb. While this specific problem is being solved by improving pilot training to comply with RAs and refining the TCAS algorithms, related problems are likely to surface as unmanned aircraft and enhanced collision avoidance technologies mix. Ensuring compatible operation also extends well beyond TCAS or aviation to many integrated sensing and decision support system applications. Lincoln Laboratory's experience with sensor fusion, decision support, and systems prototyping will greatly facilitate the path forward in these areas, and we are continually exploring new areas of complex system design.

Acknowledgments

TCAS's development spans several decades and is the product of contributions from many individuals. We would particularly like to acknowledge Thierry Arino, Ken Carpenter, Kathy Ciaramella, Roger Elstun, Stephen George, John Law, Paul Fontaine, Stuart Searight, Andrew Zeitlin, Thomas Billingsley, Barbara Chludzinski, Garrett Harris, Val Heinz, Katherine Sinclair, and David Spencer. This work was funded by the Federal Aviation Administration and by the U.S. Air Force.

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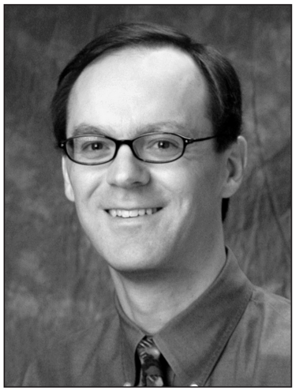

JAMES K. KUCHAR
is an assistant leader in the Surveillance Systems group, where he oversees surveillance and safety programs spanning civil and homeland defense mission areas. From 1995 to 2003, he was an MIT faculty member in the Department of Aeronautics and Astronautics. While at MIT, he focused on decision support system research with topics including TCAS, parallel runway approaches, terrain avoidance displays, and automobile warning technologies. He has S.B, S.M., and Ph.D. degrees in aeronautics and astronautics from MIT, and he has authored more than sixty journal articles and refereed conference papers. He has been a private pilot since 1995, and believes he has not yet triggered a TCAS alert.

ANN C. DRUMM
is a staff member in the Surveillance Systems group. She received a B.A. degree in mathematics and computer science from Miami University (Ohio) in 1969. She joined Lincoln Laboratory in 1969, and became a member of the Air Traffic Control division when it was formed in 1970. She was part of the team that developed the software for the FAA's first prototype Mode S sensor. She developed the protocols for TCAS air-to-air coordination, a process used worldwide to ensure that TCAS aircraft encountering one another select compatible maneuvers. She has served as technical lead for the Lincoln Laboratory FAA programs in Mode S Data Link, Automatic Dependent Surveillance-Broadcast (ADS-B), and TCAS. Her current work involves airspace monitoring to assess the performance of TCAS in the United States and investigation of TCAS on unmanned aerial vehicles.