Development and Operation of the Traffic Alert and Collision Avoidance System (TCAS)

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Invited Paper

This paper describes the development of the Traffic Alert and Collision Avoidance System (TCAS), provides a description of the TCAS II system operation, offers results of operational evaluations conducted in cooperation with Piedmont, United, and Northwest Airlines, and finally provides the status and progress of the TCAS implementation.

TCAS is the culmination of more than 30 years of work by the aviation community to develop a viable collision avoidance system to complement the Federal Aviation Administration's ground-based air traffic control (ATC) system. In recent years this effort has focused on concepts that make use of the radar transponders carried by aircraft for ground ATC purposes. A transponder-based collision avoidance system has the advantage that it can provide immediate protection against the vast population of aircraft already equipped with either the current Air Traffic Control Radar Beacon System (ATCRBS) transponder or the new Mode S transponder.

The TCAS concept encompasses a range of capabilities including TCAS I, which provides traffic advisories (bearing, range, and relative altitude) to assist the pilot in visually acquiring the threat aircraft, TCAS II, which provides traffic and resolution advisories (recommended escape maneuvers) in the vertical plane, and TCAS III, which provides traffic and resolution advisories in both the vertical and horizontal planes.

Introduction

The development of an effective airborne collision avoidance system has been a goal of the aviation community for many years. In 1955, at a joint meeting of the Radio Technical Commission for Aeronautics (RTCA) and the predecessor of the Institute of Electrical and Electronics Engineers, the scheduled airlines, working through the Air Transport Association (ATA), issued a request for the electronics industry to develop an Airborne Collision Avoidance System (ACAS) for use by airline and other aircraft. The airlines felt the need for a viable collision avoidance system to serve as a complement to the Federal Aviation Administration's (FAA) ground-based ATC system and to provide aircraft separation assurance in airspace outside areas of radar coverage. After two airliners collided over the Grand Canyon in 1956, the pace to develop a collision avoidance system suitable for national implementation intensified.

For even the simplest collision avoidance system, the magnitude and complexity of the problem and the systems requirements were not fully appreciated until after rigorous operational analyses were completed during 1956–1960. These studies led to the conclusion that the only feasible approach to the development of a collision avoidance system was through the application of cooperative techniques. That is, the collision avoidance system operation is dependent on the intruder aircraft having suitable equipment to enable the system to acquire, track, and evaluate the hazard [1].

From 1956 to 1969, the aviation industry explored the collision avoidance problem and developed a number of concepts. In 1959 the Collision Prevention Advisory Group (COPAG) was formed under FAA sponsorship. The group, in addition to monitoring the development efforts by industry, began to develop collision prevention concepts of its own. In the late 1960s several manufacturers began the design and development of ACAS units.

From 1972 to 1976, systems developed by Minneapolis-Honeywell, the Radio Corporation of America, and McDonnell-Douglas were flight tested under FAA sponsorship. The systems developed by Minneapolis-Honeywell (AVOIDS) and the Radio Corporation of America (SECANT) were interrogate-transpond systems. That is, the AVOIDS and SECANT ACAS interrogated identical units in the intruder aircraft. Altitude was determined from the received reply; range was determined by measuring the time elapsed from the interrogation signal to receipt of the reply. The ACAS manufactured by McDonnell-Douglas was based on time-frequency technology.

In the time-frequency system, all aircraft are synchronized in both time and frequency by extremely accurate oscillators on board the aircraft. Each aircraft is assigned a specific time slot of a few milliseconds in each one-second interval to transmit its signal, which contains its encoded altitude. In such a synchronized system, the time of transmission and the time of arrival are accurately known at the receiving point. Thus the range, which is proportional to

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the time difference, could be calculated. As the frequency of the transmitter is known very precisely, any difference between the measured frequency of the received transmission and the known frequency of the transmitter is proportional to the radial component of relative velocity between the transmitter and the receiver.

Thus, all of the systems provided range, range-rate and altitude information so that appropriate calculations could be made to determine the severity of the threat. All three systems generated warnings when the ratio of range over range-rate was less than a threshold value, usually 30 s. This ratio—the time before collision of two aircraft on collision course—was called TAU; it is still the basic parameter used in the collision avoidance logic. This TAU-based collision avoidance logic, developed by the ATA, is described in [2].

The tests concluded that all three systems required further work to correct false alarm problems in dense terminal traffic and to avoid electromagnetic interference with existing radio altimeters on board the aircraft [3].

The development of the Beacon-based Collision Avoidance System (BCAS) was initiated in 1974 to capitalize on the large investment in airborne transponders that were used in the Air Traffic Control Radar Beacon System (ATCRBS) to locate and track aircraft from the ground ATC facility. The concept of using the ATCRBS transponder as the cooperative element in the collision avoidance system was attractive from the standpoint that its selection would provide protection from the largest possible percentage of potential collision threats, would have less regulatory impact, and would be immediately effective for the BCAS aircraft against all threat aircraft having altitude encoding transponders. By 1976, work on the BCAS concept had progressed to the point where its feasibility was established and further work on the earlier ACAS concept was discontinued [4].

From the initial concept, a feasibility model of BCAS was conceived and breadboarded in early 1975. This early period in the development of BCAS extended for a little over three years, into 1978, during which time the major components of the system were formulated and tested. The initial operational concept was to have BCAS provide protection in the low-density en route airspace, and to have a separate ground-based collision avoidance system provide protection in the dense terminal areas. This system was called Automatic Traffic Advisory and Resolution Service (ATARS).

Surveillance was of major concern during the early years. The most difficult problem was that of synchronous garble, the overlapping of replies from many ATCRBS-equipped aircraft that were approximately the same distance away from the BCAS aircraft responding to the same interrogation. Three methods were proposed for alleviating it: advanced processing techniques; variable power interrogations (called whisper-shout); and directional interrogation. The first two of these were tried out in the feasibility model. The successful completion of the flight tests provided the confidence that the BCAS approach was feasible with the computer technology available at that time.

While feasibility of surveillance received the greatest emphasis during this period of the program, the foundation was also being laid for developing the collision avoidance system (CAS) logic. Starting from the concepts of the collision avoidance logic developed by the ATA, the skeletal framework for a vertical-only logic was developed for BCAS. This logic was coded into the Air Traffic Control Simulation Facility at the FAA Technical Center; the operational environments of both Chicago and Knoxville were simulated. Furthermore, the cockpit simulator (GAT II) at the Technical Center was used, together with a 360-degree visual display capability to obtain a preliminary assessment of pilot reaction times to BCAS advisories and display devices [5], [6].

The decision to proceed with the implementation of an aircraft collision avoidance concept called TCAS was announced on June 23, 1981. The concept was based on previous development efforts with BCAS and with the discrete address communications techniques utilizing the new Mode S beacon system message formats. TCAS provides additional capabilities beyond those provided by BCAS, namely: the ability to provide collision protection in the highest aircraft densities; the provision of an auxiliary display of traffic information, called the traffic advisory display; and the ability to alert the pilot to the presence of non-Mode C aircraft (aircraft with transponders but without altitude reporting capability) [7].

The FAA approach to TCAS was to develop a family of onboard collision avoidance systems, demonstrate the operational and technical feasibility of the concept, and support the development of national/international standards for the equipment. The TCAS Program consists of three elements: TCAS I, TCAS II, and TCAS III.

TCAS I, the least expensive option, is intended for installation in general aviation, corporate, and commuter airline aircraft. A TCAS I unit will alert the flight crew of an intruder aircraft by generating a traffic advisory.

TCAS II equipment, intended for installation in transport category aircraft, provides traffic advisories and also computes resolution advisories to indicate in which direction the aircraft should maneuver in order to avoid a collision. TCAS II equipment generates resolution advisories in the vertical plane (climb/descend).

TCAS III equipment, intended for installation in transport category aircraft, is designed to generate traffic advisories and resolution advisories in both the horizontal (turn right/turn left) and vertical planes.

Description of TCAS II

Fig. 1 shows the functional elements of TCAS II. The interrogator is actually a bimodal system, time sharing its interrogations of ATCRBS and Mode S transponders. The TCAS receiver likewise is bimodal, providing reports to the computer on the altitude, range, and bearing of both types of transponders. These reports are tracked, and the other aircrafts' altitude-rate and range-rate are derived and, together with the altitude and range, are passed on to the CAS logic, where threat detection, resolution, and display are handled.

The transponder in the TCAS aircraft is a Mode S unit, to enable high integrity communication between two conflicting TCAS aircraft for the purpose of coordinating their collision avoidance maneuvers.

The typical encounter with a Mode C, ATCRBS equipped intruder would provide a Resolution Advisory (RA) if both a range threshold and an altitude threshold are crossed. The right-hand column in Fig. 2 shows that if either the time to closest approach or the current range becomes too low (approximately one-half min or one-half nmi) the range

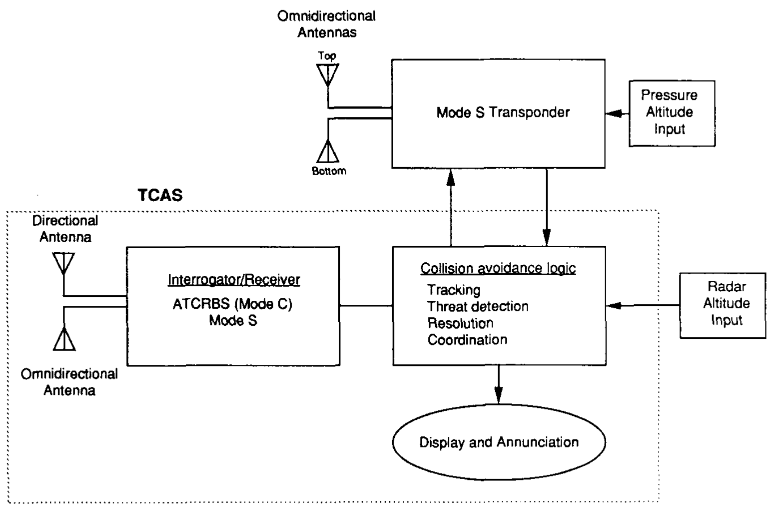

Fig. 1. TCAS II functional elements.

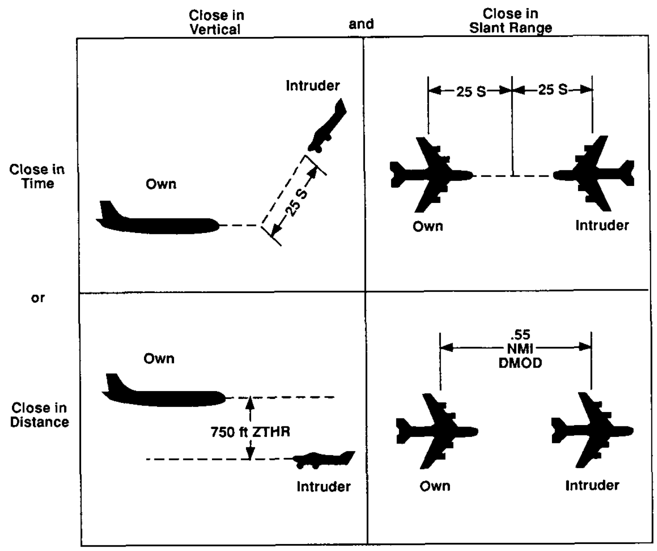

Fig. 2. TCAS II threat detection criteria.

threshold is crossed. Similarly, the left-hand column shows that if either the time to coaltitude or the altitude separation are too low (approximately one-half min or 750 ft) the altitude threshold will be crossed.

Surveillance

The requirements for TCAS to operate in aircraft densities of up to 0.3 aircraft/nmi^2 (24 aircraft within 5 nmi of the TCAS aircraft), to provide direction-finding capability to support the display of traffic, to operate completely independently of the ground ATC system, and to operate without interference to the ground ATC system placed new stringent demands on the airborne surveillance system for TCAS.

The design of the air-to-air surveillance function of TCAS II builds on the previous development of BCAS by the addition of a number of improvements to accommodate higher aircraft densities. The BCAS design was intended for operation in densities of up to 0.02 aircraft/nmi^2. With the change from BCAS to TCAS, the design goal for aircraft density was changed to include the major metropolitan areas plus an allowance for future growth in air traffic. As mentioned previously, a density of 0.3 aircraft/nmi^2 was adopted as the specific goal.

In changing the BCAS design to accommodate this higher density, a number of issues had to be considered. Primary among these was the issue of *synchronous garble* in Mode C (Fig. 3). Here, TCAS is performing surveillance using omnidirectional interrogations. When received, the replies

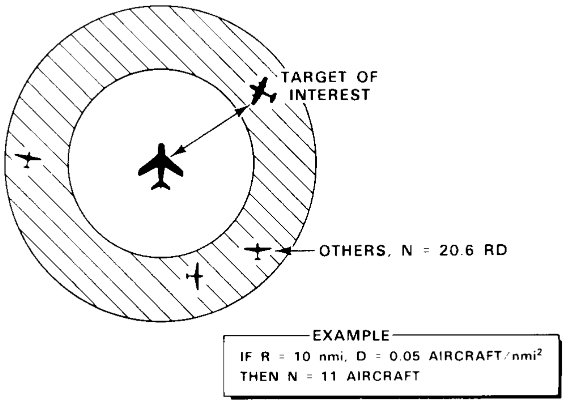

Fig. 3. ATCRBS synchronous garble.

from a particular aircraft of interest will be overlapped by replies from other aircraft at approximately the same range. This is called synchronous garble because the desired reply and the interfering replies are triggered by the same interrogation. If, for example, the aircraft of interest is at a range of 5 nmi and the aircraft density is 0.1 aircraft/nmi^2, then the average number of other aircraft near enough in range to cause synchronous garble is 11. It is impossible to reliably detect a reply in the presence of 10 overlapping replies.

To enable TCAS to operate in the high aircraft density required, two techniques were investigated and incorporated in the TCAS design to reduce the effects of synchronous garble: whisper-shout and directional interrogations.

Whisper-Shout

The principal technique for controlling synchronous garble is the use of variable power levels for ATCRBS interrogations called whisper-shout. The purpose of whisper-shout is to partition or subdivide the set of synchronously garbling aircraft so that fewer will reply to any one interrogation.

The simplest form of whisper-shout is illustrated in Fig. 4. In this 2-level whisper-shout sequence, the purpose is to divide the synchronous garble population into two approximately equal subsets. The first interrogation is transmitted at a relatively low power level so that approximately half of the aircraft in the synchronous garble range band will receive it above threshold. Thus only these will reply to the first interrogation, and the synchronous problem will be reduced by a factor of about 2 in this first reply listening period. The second interrogation is transmitted at full power so as to be detectable by all of the aircraft. But this interrogation is preceeded by an additional pulse, denoted S1, of power level nearly equal to that of the first interrogation. The purpose of S1 is to trigger the suppression function in those transponders that replied to the first interrogation. Thus, the first set of aircraft will not reply again, and so in the second listening period, the synchronous garble problem will again be reduced by a factor of about 2.

The improvement in performance between a single normal interrogation and a sequence of whisper-shout interrogations is illustrated in Fig. 5.

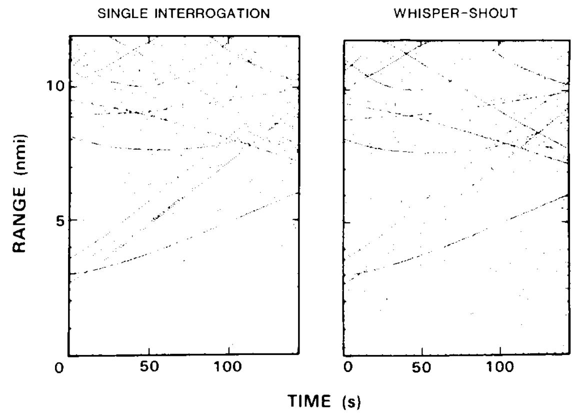

Fig. 5. Improvements due to whisper-shout.

Directional Interrogation

The use of a directional interrogation is another technique for reducing ATCRBS synchronous garble in the highest density environments. The directional interrogation only elicits replies from the cross-hatched region (Fig. 6). This reduces the size of the reply region and hence the number of aircraft that reply to any interrogation.

Since coverage must be provided in all directions, multiple beams are used to elicit replies from all aircraft in the

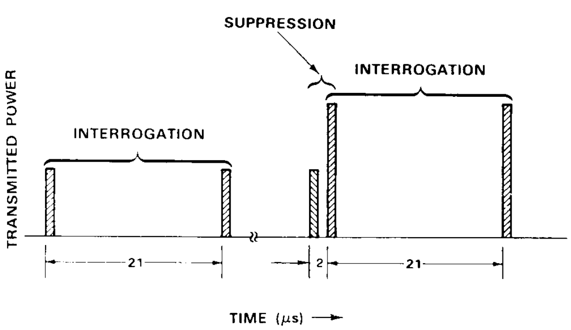

Fig. 4. Whisper-shout technique.

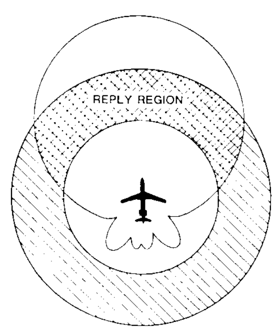

Fig. 6. Directional interrogation.

vicinity of the TCAS II aircraft. Care is taken to overlap the beams so that gaps in coverage do not exist at the beam edge.

Mode C Tracking and Correlation

TCAS augments measurements of intruder range and altitude with recursively derived estimates of the associated rates. The estimation, or tracking, requires an association of the replies with the originating aircraft. The association process, called reply correlation, is based on geometry, given the absence of any aircraft-identifying reply features. Reply correlation has two phases: the initial recognition of a previously unknown target, and the correlation of replies with existing target tracks.

Existing track positions are predicted to the time of the whisper-shout interrogation sequence (the "scan" time) and compared to the measured positions of the received replies. A reply is correlated to a track if the reply range is within 570 ft of the prediction, and the altitude is within 100 ft (or 200 ft if the 100 ft test fails). Tracks finding no correlating reply for 6 scans are terminated.

The replies that did not correlate to existing tracks may be "fruit" replies (received by TCAS, but elicited by other interrogators), TCAS-elicited replies that failed to correlate due to errors in the track position or the reply measurement, or TCAS-elicited replies from aircraft not currently in track.

The track initiation process attempts to form new tracks from the uncorrelated replies left over from the three most recent scans by identifying reply triplets that lie in a straight line (within 312 ft) having a range rate of 1200 knots or less. The three replies' altitude codes (11 bits each) are examined in each of the 11 bit-positions. If the three replies have the same code bit values in the 8 most significant positions, or in 7 of those 8 and in 1 of the 3 least significant positions, then a tentative track is formed. The tentative track will participate in the reply correlation process on future scans and become eligible for use by the collision avoidance algorithm if a correlating reply is found within 6 scans.

Non-Mode C Tracking and Correlation

The replies received from transponders that are not equipped with altitude encoding devices have no bits set in the 11 altitude code bit positions, and are referred to as "altitude-unknown" or non-Mode C replies. They can be correlated into tracks almost as reliably as Mode C replies provided that the predictions are made on the basis of alpha, beta, gamma tracking of the squares of the range measurements. In straight flight, the usual situation, the square of the range follows a parabola (Fig. 7). The predictions made by such a parabolic tracker enable a reduction of the range correlation windows from 570 ft to 250 ft, in most cases. The tracker includes provisions for increasing the window size when the reply data is sparse, and during maneuvers by the TCAS or target aircraft.

Mode S Surveillance

Mode S transponders each have a unique, permanently assigned identification number (ID), which is included in the reply whenever an interrogation addressed to that ID is received. The presence of the ID simplifies the correlation and tracking processes. On the other hand, the interrogation process is complicated by the requirement to minimize the number of such uniquely addressed interrogations so that TCAS does not overload the 1030/1090 MHz channels. TCAS Mode S interrogation activity is minimized by interrogating each target at a rate proportional to a coarse measure of that target's potential to be a collision threat.

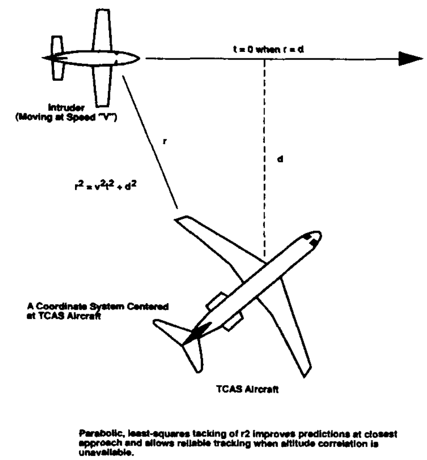

Fig. 7. Tracking altitude-unknown targets.

Mode S transponders make their presence known to ground-based and TCAS interrogators by periodically emitting "squitter replies" which contain the target's ID, but not the altitude. TCAS spends a substantial amount of time listening for squitters, and during which it coincidently receives Mode S fruit replies (that were elicited by other interrogators) containing ID plus altitude. The rate of squitter reception (which is usually lower for more distant targets), along with altitude information obtained from fruit, is used to determine whether a target warrants interrogation to determine its range. When the so-determined range is sufficiently close, the target will be continuously interrogated at a suitable rate, using a power consistent with the range. The general nature of Mode S interrogation rules is illustrated Fig. 8.

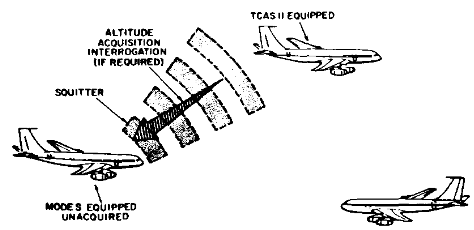

Fig. 8. Mode S target acquisition by TCAS.

The range and altitude accuracies (quantizations of 62 ft and 100 ft, respectively) available from Mode C and Mode S transponders are sufficient for vertical escape maneuvers when measurements are made once per second. Pilots can augment the see-and avoid function using the cockpit display of traffic provided by bearing measurements quantized to half quadrants.

Interference Limiting

Since the same 1030/1090 MHz channels are used by the ground ATC system, TCAS interrogations and the resulting replies must not overload the channels. Consequently, TCAS interrogations are restricted in power and rate to levels that result in an insignificant increase in channel activity over that caused by the ground-based ATCRBS and (future) Mode S interrogators.

The TCAS interference-limiting function is implemented by each individual TCAS unit based on a count it makes of (full-power) "TCAS broadcast interrogations," which are made once per second by all TCAS units. The count indicates the number of other TCAS units within about 30 nmi (the maximum range of 250-W transmissions considering the average receiver Minimum Triggering Level [MTL]). The TCAS unit then adjusts its own interrogation activity so that, in conjunction with similar adjustments by the other units, the ensemble of interrogations causes no degradation to either the ground or TCAS systems.

The principle adjustment is to reduce the interrogation power, which reduces the surveillance range and thus the maximum closing speed for which collision protection can be provided. TCAS normally provides protection against head-on collisions by aircraft closing at 1200 knots. Fortunately, the velocity protected against decreases inversely with the square root of the count of nearby TCAS units (when over 16), and always remains greater than the closing speeds actually experienced, which are regulated in high-density airspace. In all future projections of air traffic densities and TCAS deployments, the collision protection will remain effective.

Multipath Effects Reduction

Measurements made during TCAS development showed that secondary radar submicrosecond interrogation and reply pulses could be sent between two aircraft using conventional L-Band antennas, receivers, and 250-W transmitters, provided that the ground-reflected pulses, which were often specular and usually received at a lower level than the direct pulses, fell below the receiver MTL. Mode S interrogations using Differential Phase Shift Keying (DPSK) were found to be relatively resistant to ground reflections.

Since modifications of existing ATCRBS transponder receivers and transmitters was impractical, a sequence of variable-power Mode C interrogations was adopted in the TCAS design to ensure that each transponder would receive at least one interrogation per second in which the direct pulses were above threshold, while the reflected pulses were below. On the reply link, the TCAS receiver adopted a Dynamic MTL (DMTL) which, in response to the first pulse in a reply, is quickly raised sufficiently to discriminate against the delayed and lower powered reflections, as shown in Fig. 9. The substantial improvement that DMTL provides for reply pulse decoding is evident in Fig. 10.

TCAS II Surveillance Performance Assessment

TCAS II performance was assessed in a number of ways, including airborne measurements focusing on individual techniques and simulation of the Mode S surveillance processor. A primary step in the performance assessment process was a series of airborne measurements in the Los Angeles Basin aimed at evaluating the Mode C surveillance design as a whole. The LA Basin is known to have the highest density of aircraft in the United States. These tests were conducted in a Boeing 727 equipped with an experimental TCAS II unit having a 4-beam directional interrogator as well as the other TCAS II design characteristics listed above.

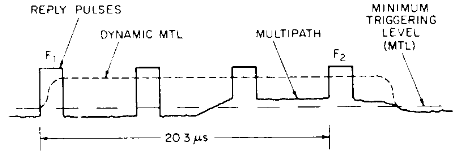

Fig. 9. Dynamic thresholding of ATCRBS replies.

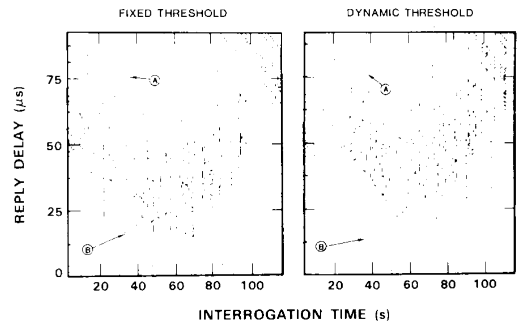

Fig. 10. Improvements due to dynamic thresholding.

Performance was assessed by analyzing the data in several ways. One study focused on aircraft targets-of-opportunity that passed by in a relatively close encounter. Surveillance reliability was good. In such cases the percentage of time during which the target aircraft was in track was about 97 percent (during the 50-s period prior to the point of closest approach in each encounter).

In a second study, the detailed pattern of replies was analyzed to derive a quantitative estimate of the effectiveness of 4-beam directional interrogation in alleviating synchronous garble. These results show an improvement factor of 2.4, which is in agreement with the amount predicted according to the geometry of directional interrogation.

A third study was statistical, based on all of the aircraft that passed within 5 nmi in range while being within $\pm 10°$ in elevation angle. The purpose of this study was to determine the functional dependence of surveillance reliability on aircraft density. The results indicate that there was not a significant degradation in performance as a function of density. The density values experienced in the LA Basin during these tests, although very high in an absolute sense, were not high enough to significantly degrade surveillance performance.

A TCAS II design that incorporates a top-mounted directional antenna and a bottom-mounted omnidirectional antenna and that employs a 24-level whisper-shout sequence and proven Mode S surveillance algorithms is capable of excellent surveillance reliability in today's high-density Los Angeles Basin environment, and is predicted to continue to provide excellent performance in similar environments through the end of the century without detectable degradation to the performance of the ground-based beacon surveillance system [8].

Development of Collision Avoidance Logic

The basic concept for a collision avoidance function is the notion that the pilot should be alerted to a dangerous situation in time for him to take remedial action by either turning the aircraft or changing its altitude. The obvious but interesting characteristic of this concept is that it is independent of the intruder's speed. That is, 30 s to collision provides the same time for reaction whether the intruder is approaching at 100 knots or 1000 knots (the ranges at which the alarms are given are, of course, quite different). Furthermore, the time parameter can easily be adapted to the airspace in which the aircraft is flying, longer times being made available, for example, to accommodate the larger errors that occur in altimetry at the higher altitudes.

When the early collision avoidance system, ACAS, was conceived, it provided Resolution Advisories (RAs) only. These RAs were generated whenever TAU was less than a threshold value, approximately 30 s. During the TCAS development process, a modification of TAU was proposed. This modification calculates the time to approach a given separation, say one mile, rather than the time to collision, thereby providing needed protection for low closing rates, ensuring that the aircraft will not drift closer than that distance without receiving an alarm. A minor modification of that is used today [9].

TCAS II Development

A major effort was undertaken during the development of TCAS II, in which a Boeing 727 aircraft, normally used for experimental and flight safety applications, was outfitted with a TCAS Experimental Unit developed by MIT Lincoln Laboratory, carrying the CAS logic developed by The MITRE Corporation, and flown on a "tour" across the country. Prior to that effort, however, it was important that the various threshold parameters that defined the operation of the system be set to realistic values. As a step in addressing this task, MITRE reduced 65 h of ATC data from the Houston radar. Houston was selected for this study because its terminal area included a large international airport (Houston Intercontinental), a large general aviation airport (Hobby), and an active military airport (Ellington Air Force Base). As a result of this effort, nominal settings had been assigned to all logic parameters by the time the flights were conducted, and the concept of Sensitivity Level Control had been established and validated [10]. The latter involves optimization of parameters according to the airspace, so that the trade-off between protection and unnecessary alarms could be different in low-altitude approach-and-departure airspace from that in high-altitude cruise airspace.

When the cross-country "tour" was conducted, flying to 18 major airports in a period of 3 weeks, the operational results were remarkably close to those predicted from the Houston study.

Protection, too, was repeatedly evaluated by flying planned encounters in "sterilized airspace" at the FAA Technical Center at Atlantic City, NJ, and comparing the results with simulations run at both the Technical Center and at The MITRE Corporation. Major operational implications arose from these tests. For example, prior to this time all collision avoidance displays, from the earliest ACAS, were of the simple Resolution-Advisory-only type—typically an arrow on the Vertical Speed Indicator telling the pilot to climb or descend. The cross-country tour, however, demonstrated how useful even a rough plan position display would be, especially to point out non-Mode C aircraft [11]. Indeed, the Traffic Advisory Display later became central to all subsequent collision avoidance work. As time went on, the integrated concept was developed of 1) Traffic Advisories, to alert the pilot to the situation so that he could often visually locate the intruder and respond appropriately; 2) Resolution Advisories, to provide the best information to escape in case the pilot could not see the intruder; and 3) Proximity Advisories, to display all nearby aircraft, whether they constituted a threat or not, whenever a Resolution Advisory was posted. The latter would properly represent the visual scene in case there were several aircraft in the field.

The end of the development phase was signaled by the completion of the Piedmont Phase I flights [12]. Previously, the FAA had procured a few TCAS units, awarding the contract to what is now a subsidiary of the Honeywell Corp. Piedmont Airlines agreed to carry the equipment, which included a data recorder, on its normal operational flights, but not to let the TCAS displays be seen or heard by the pilot. This evaluation provided an abundant source of data for completing the system design. For example, the concept of using an input from the radar altimeter to screen out replies from aircraft on the ground—formerly quite a nuisance near large airports—originated as a result of these flights. This also was the time during which performance limits in the logic were developed. That is, if the aircraft is at its highest altitude, and cannot climb, the escape choices must be between the better of "stay level" or "descend".

Operational Evaluation

Many details of an operational nature had to be addressed in the TCAS development program. TCAS is a "first" in a class of avionics that actually advises a maneuver, rather than the more conventional role of showing the situation to the pilot for his evaluation (weather radar, for example). Thus, the integrity of the software and hardware and the role of the pilot had to be developed. Questions of pilot immunity, should TCAS give the wrong answer, had to be addressed. How would the pilot and controller handle a TCAS-suggested maneuver? What kind of training must the pilot receive before he can use the system in passenger-carrying service?

A major portion of the TCAS development effort was devoted to answering these operational questions. All the experience obtained at the FAA Technical Center, MITRE, and MIT Lincoln Laboratory were brought to bear. The airlines and the pilot community (subcommittee of RTCA) were also deeply involved.

The activities that addressed the operational issues were the Piedmont Airlines Phase II TCAS evaluation and the Limited Installation Program (LIP), [13]. The Piedmont Phase II evaluation was conducted to assess the impacts of TCAS on flight crew workload and on the ATC system, and to obtain flight crew comments on TCAS design parameters and cockpit displays. The evaluation was conducted on a Boeing 727 aircraft operating in revenue service with Piedmont Airlines. The program started out gradually; the pilot could maneuver in response to a TCAS resolution advisory only if he could see the other aircraft. After a satisfactory trial period, a maneuver was permitted only if the pilot could "clear the airspace" into which he was heading.

Quantitative data on TCAS performance were collected to characterize the location and frequency of advisories; qualitative data were collected from flight crews and cockpit observers. Minor operational anomalies were identified and changes to operational procedures or the TCAS logic were implemented. The Piedmont Phase II evaluation was a real milestone in the achievement of a working system, not the least of which was the development and validation of a pilot training program for TCAS [14]. In the Limited Installation Program TCAS II equipment from several manufacturers (Bendix; Honeywell) was flown on several airlines (United; Northwest). Approval was obtained to operate the system in revenue service in all flight regimes and in all weather conditions. During the evaluations, the systems were operated for more than 4000 hours. The results of the evaluations indicated that TCAS II is safe and operationally effective

- is suitable for routine airline operations
- operates under all weather conditions
- increases pilot confidence while operating in the ATC system
- complements and enhances routine cockpit duties.

Interaction with ATC

ATC interaction has been of concern in the design of TCAS since its early stages. Reference has already been made to large-scale ATC simulations in the Chicago and Knoxville terminal areas. These results, allaying fears that there would be too many alerts, were borne out by flight experience (Piedmont Phase I, Phase II, and the LIP). The normal per-aircraft rates were roughly once in 20 h for a Resolution Advisory, and once in 5 h for a Traffic Advisory. In addition to the low TCAS Resolution Advisory rate, the amount of displacement required to resolve an encounter was usually minimal. Well over 90 percent of the Resolution Advisories required a displacement of less than 300 ft.

A specific study was undertaken of the Chicago terminal area for instrument weather conditions (so-called Instrument Meteorological Conditions, or IMC) [15]. There, it was found that these translated to about one corrective Resolution Advisory (recommendations that the flight path be altered) per hour for the entire facility, and about one in 6 h per sector controller, assuming all aircraft are equipped with TCAS. The possibility of a domino effect was also evaluated in the IMC study by both observing the behavior of aircraft in a holding pattern and by artificially compacting the holding pattern to load it up with the maximum number of aircraft, all phased to be over each other at the same time. It was found that instead of generating an unstable domino situation, the TCAS Resolution Advisory would actually bring an accidentally deviating aircraft back to its clearance. The multi-aircraft feature in the TCAS logic tended to prevent any such movement from propagating to additional aircraft.

System Safety Study

Because TCAS is intended to provide emergency information to the pilot in time to avert an impending collision, a quantitative evaluation of its performance, advantages and limitations with respect to the improvement of aviation safety is essential; a TCAS II System Safety Study was performed to satisfy this need [16]. The study was initiated as a means for formalizing several independent ongoing analyses by the aviation community. A team, headed by MITRE, developed a comprehensive methodology for the analyses of TCAS safety, in addition to providing the quantitative evaluation of TCAS performance. Five reviews of the progress of the study were held during the 10-month study period, in which a broad spectrum of the aviation community participated. This participation not only provided feedback to the study team but also assured that all major topics of interest were considered.

There were actually three different studies conducted over a period of time. The basic study was reported in 1983, and addressed the safety of aircraft with TCAS II in normal air passenger service. The second study, published in 1985, addressed the same question, but assumed that the aircraft was at all times in instrument weather conditions (IMC). The third study, published in 1988 [17], is an update to the earlier works, providing the latest information on aviation altimetry errors, on the maneuvering of aircraft in terminal areas, and on the most recent improvements to the collision avoidance logic.

When the 1983 study was conducted, as much "real world" data was used as was available, but often not much was available. For example, the state of knowledge on the accuracy of general aviation altitude reporting (Mode C) was very limited. The data used were mainly the specifications to which the manufacturers built their instruments. By 1988 two major measurement programs had been conducted that greatly enhanced this knowledge in U.S. airspace. As a result, these errors were found to be considerably lower than earlier estimated.

Similarly, when accounting for a non-TCAS intruder suddenly maneuvering such as to thwart a Resolution Advisory by the TCAS aircraft, the only data available in 1983 was that obtained from just under 1000 h of the Piedmont Phase I flights. By 1988, a large data base of well over 10 000 flight hours of radar-recorded data was analyzed by the United Kingdom. This European data base disclosed considerably more maneuvering than had been earlier observed. However, the improvements to the collision avoidance logic had also made the system considerably more robust to such maneuvers.

When all the new data were analyzed with all of the new collision avoidance logic, the results remained essentially unchanged. Fig. 11 provides an overall representation. The probability of a critical near midair collision occurring to an air carrier aircraft today, without TCAS, is represented by the column on the left. The next column shows how that would be altered (the Risk Ratio) when TCAS is carried on the aircraft. The unresolved component is caused mainly, but not entirely, by aircraft flying without transponders and Mode C altitude encoders. The induced component is just about equally distributed between altimetry effects and maneuvering intruder effects. The third column shows what would be expected with the newly enacted Mode C rule,

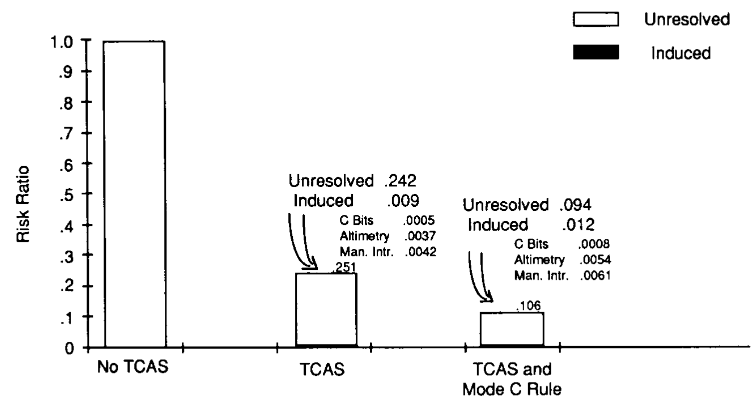

Fig. 11. Comparison of results of system safety study.

which extends the requirement for Mode C to all aircraft below 10 000 ft and within 30 nmi of a terminal control area or a terminal radar service area. Thus TCAS can be expected to resolve 75–90 percent of the "critical" near midair collisions (thereby presumably of actual midair collisions), while causing them on its own at a rate of about 1 percent of the current rate.

Within these calculations is the basic consideration that, if the TCAS pilot sees the other aircraft in time, he will maneuver to avoid a collision regardless of an erroneous TCAS display. Even that assumption, however, was qualitatively treated by enabling one to assign a failure fraction to it and then to evaluate the consequence. Nevertheless, it is obvious that one important factor in the System Safety Study had to do with the pilot's ability to use the Traffic Advisory display to help him visually acquire the other aircraft. This study, performed at M.I.T. Lincoln Laboratory, and its results in the System Safety studies strongly validate the use of the Traffic Advisory display, which is now an inherent part of TCAS [18]. The ability to use the results of the System Safety calculations in evaluation of such features as well as evaluating alternative logic concepts proved to be a valuable adjunct to the study itself.

International Standards

The International Civil Aviation Organization (ICAO) established the Surveillance Improvement and Collision Avoidance Systems Panel to develop international Standards And Recommended Practices (SARPS) for collision avoidance systems and the Mode S surveillance system. ICAO has noted the development of TCAS II and published a worldwide information circular describing TCAS (Circular 195-AN-118). This circular provides *de facto* recognition of TCAS II as the system under consideration for international adoption and is a prerequisite for the ICAO SARPS.

TCAS Implementation

The basis for TCAS implementation in the United States is Public Law 100-223. This law, which became effective December 30, 1987 requires the FAA to complete the development of TCAS II within 18 months and the airlines to complete the installation of TCAS II on all airplanes with more than 30 passenger seats within 30 months.

After passage of Public Law 100-223, questions arose about the safety implications of the certification and implementation schedule for TCAS II contained in the law. The Subcommittee on Aviation of the Senate Committee on Commerce, Science, Technology, and Transportation asked the Office of Technology Assessment (OTA) to assess these implications and report in early 1989.

The OTA found that aviation safety would best be served by introducing TCAS II on commercial aircraft as soon as possible, by requiring a phased implementation schedule, and by providing for a structured evaluation program carried out jointly by industry and the FAA to oversee the first year of operation. Legislation is currently pending in the Congress to revise Public Law 100-223 to incorporate recommendations of the OTA.

To implement the provisions of P.L. 100-223 the FAA issued the Final TCAS Rule January 5, 1989. The rule required the installation and operation of TCAS II in airplanes with more than 30 passenger seats by December 30, 1991. The rule also requires the installation and operation of TCAS I units in turbine-powered airplanes with 10 to 30 passenger seats by February 9, 1995.

After passage of the TCAS II legislation currently under consideration in the Congress, the FAA will revise the implementation schedule contained in the Final TCAS Rule.

There is a significant amount of activity under way related to the implementation of TCAS. An advisory circular has been developed and published to provide guidance for the installation and operational approval of TCAS installations. In addition, crew training programs have been developed and validated, and operational procedures approved and validated.

Conclusions

The development of an airborne collision avoidance system that is fully compatible and integrated with the conventional air traffic control system is now completed. The design assures that aircraft equipped with TCAS avionics will immediately receive protection from midair collisions due to the fact that most aircraft are required to carry altitude-reporting transponders in most of the airspace in which airline aircraft operate. The system has demonstrated its effectiveness in reducing the potential of midair collisions in operational evaluations conducted on airline aircraft in actual line operations. The implementation of the system is well under way, with manufacturers currently producing equipment and airlines preparing to install equipment to meet the installation requirement specified in Public Law 100-223.

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