AIRBORNE COLLISION AVOIDANCE SYSTEMS - THE UK EXPERIENCE

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ABSTRACT

The history of the development of ACAS is briefly reviewed. The forms of ACAS are listed before concentrating on TCAS II which is the US implementation of the form of ACAS currently being developed for public transport aircraft. The theory behind the logic used in TCAS II is outlined. UK inputs to the development of modification of the logic are described together with work using recorded radar data to conduct safety studies. The UK operational trial of TCAS II using a British Airways Boeing 737 aircraft and Allied-Bendix prototype equipment is described together with the initial objectives and the findings. Potential benefits over and above those drawn solely from collision avoidance protection are considered.

The views expressed in the paper are those of the author and not necessarily those of the UK Civil Aviation Authority.

1. History

The reasons for developing an Airborne Collision Avoidance System have their roots in a series of mid-air collisions involving public transport aircraft which have occurred in the US over a number of years. In particular the accident at San Diego in 1978 and that at Cerritos, near Los Angeles in 1986, resulted in considerable pressure within the US for a practical system. Systems were developed which had the disadvantage that all aircraft would have to carry special equipment in order for them to be effective but later both passive and active techniques making use of the standard SSR transponder were developed. The active mode was finally progressed to an operational system initially known as BCAS (Beacon Collision Avoidance System) but subsequently renamed TCAS (Traffic Alert and Collision Avoidance System). The system is independent of ground-based systems and currently provides escape manoeuvre guidance in the vertical plane only.

The US Federal Aviation Administration (FAA) has issued a rule which mandates the carriage of TCAS by public transport aircraft of all nationalities in US airspace. For US carriers a phased implementation has been defined but for non - US aircraft with 30 seats or more, TCAS II (see below) must be fitted for operations after 31 December 1993.

2. Definitions

Before proceeding further it will be useful to define some of the more commonly used acronyms related to TCAS since they will be repeated throughout this paper:

ACAS - Airborne Collision Avoidance System - an international term used by ICAO to include all types of collision avoidance systems.

TCAS - Traffic Alert and Collision Avoidance System - the US implementation of ACAS (to date the only implementation).

TA - Traffic Advisory - warning given to crew to indicate traffic which is a potential threat - <u>used to aid visual acquisition only</u>.

RA - Resolution Advisory - warning which gives commands to limit or change vertical flight profile to avoid threat traffic.

Own aircraft - The TCAS equipped aircraft

TCAS, the US implementation of ACAS, is defined in three versions

TCAS I - gives proximity warning only,

TCAS II - gives escape manoeuvre guidance in the vertical plane only,

TCAS III - gives escape manoeuvres in both the vertical and horizontal planes.

This paper describes the UK involvement in TCAS II only.

3. Principles of TCAS II Operation

3.1 Threat Detection

TCAS II is basically an airborne secondary radar system which detects transponder equipped traffic nearby and warns pilots of potentially close encounters. Surveillance of surrounding traffic can be divided into three components, range, relative altitude and relative bearing. The logic in the on-board

TCAS II computer makes use of only the first two components. Currently the relative bearing accuracy available from airborne antennas is not sufficient to provide an accurate assessment of potential threat. The use of bearing information will be described later.

In assessing whether or not an aircraft is a potential threat an estimate of the expected miss distance is made by making use of range and range rate in the horizontal plane, and Mode C altitude data in the vertical plane. It is not possible in this paper to give a full description of the collision avoidance logic used. Detailed information can be obtained in Ref 1. Briefly TCAS II operates on a time based, rather than distance based principle. For a collision situation the time to collision can be defined as $-r/\dot{r}$. However we are interested not only in potential collisions but potential near-misses. Furthermore, any deviation from the current horizontal profiles of both own aircraft and the threat aircraft after an RA has been issued must be allowed for to some extent. TCAS has no knowledge of the future intent of either own aircraft or the intruder. The concept of tau, (τ) the time to closest approach, was introduced at an early stage in the development of TCAS. Tau is defined as:

$$\tau = -(r - Dm)/\dot{r}$$

where Dm is about 0.3nm

This form of the warning time produces a protected area which approximates to a circle of radius $V\tau$ where V is the magnitude of the relative velocity vector along the line between the two aircraft. Own aircraft lies on the circumference of the circle directly opposite the threat aircraft. The definition of τ was modified by the UK mathematician Bramson (Ref 2) to:

$$\tau = -(r^2 - Dm^2)/(r\dot{r})$$

This modification improved the detection rate at low closing speeds whilst at the same time reducing the alert rate by 10%. One problem associated with TCAS II is that of the number of nuisance warnings received. A nuisance warning may be defined as one which is generated by the logic where no real risk of a close encounter or collision exists. (See 3.2.)

The value of τ is set at 20-30 seconds for a resolution advisory (depending on altitude) and 10-15 seconds more in the case of a traffic advisory. When τ falls below the preset value the <u>range test</u> is deemed to have been passed.

In order to avoid the generation of warnings from aircraft which are well separated vertically from own aircraft an altitude test is also performed. Again details of this are given in Ref 1. Briefly an estimate is made of the altitude separation at the point of closest approach as calculated in the range test and of the horizontal separation at co-altitude. If this vertical separation is of small (typically 750 feet or less) or the range at co-altitude less than 0.4nm the altitude test is deemed to have been passed. The effect of the altitude test is to change the protected area given by the range test into a scalloped sphere as shown in Figure 1. Only when both altitude and range tests are passed is an advisory issued.

It has been mentioned that TCAS II also measures relative bearing although this parameter is not used in the collision avoidance logic. Bearing information is used only to provide information on a display in the cockpit which indicates the area in which to look in order to try and see the conflicting traffic and perhaps use normal see and avoid procedures. The nature of this display is described later.

3.2 <u>Collision Avoidance Logic</u>

Having declared an aircraft to be a threat worthy of an RA, the TCAS II logic then determines a suitable escape manoeuvre to ensure safe separation. The system assumes that the pilot will take five seconds to react to a warning and then induce a vertical manoeuvre which is in general not more than 0.25g. The system computes a vertical speed to be achieved which must not be more than 1500 ft per minute or, if the aircraft is currently climbing or descending at more than 1,500 ft per minute, assumes that the current vertical speed will be maintained. The system aims to produce a vertical separation of not less than 400 ft at the point of closest approach. Once the avoidance manoeuvre has been initiated the system can indicate its success by a softening of the command eg from "climb" to "do not descend" and finally to "clear of conflict". At this stage the aircraft is free to return to its original flight profile. It is possible in some circumstances for TCAS to change its mind and issue a climb followed by a descent or vice versa. This happens normally when the intruder changes its own vertical flight path after the RA has been issued. Under these circumstances increased g forces can be accepted (0.3g) and higher vertical rates (up to 2,500 ft per minute), may be commanded.

It must be stressed that TCAS II can issue RA's when there is no actual risk of a collision or a close encounter. This is an inherent characteristic which results from the inability to make use of bearing data and the fact that the system has no knowledge of the future flight profiles of either the threat or own aircraft. This must be borne in mind when considering alert rates in relation to the efficiency of any ATC system.

3.3 - Coordination for between two TCAS equipped aircraft.

If both own aircraft and the intruder are TCAS equipped it is important to ensure that RA's given to each pilot are compatible. To this end there is co-ordination between the two TCAS computers via an SSR Mode S link. This link provides the means of a dialogue whereby it is ensured that (say) if one aircraft is instructed to climb, the other is instructed to descend, or at least maintain level flight. The co-ordination logic is very complex but in its simplest form it deems that the first TCAS computer to generate an escape manoeuvre is free to advise that manoeuvre to the crew and the other computer must generate a complementary advisory accordingly.

4. TCAS Equipment

4.1 Components

The basic equipment to be fitted to an aircraft to enable it to use TCAS II consists of:-

- Mode S SSR transponder and associated antennas (necessary for TCAS - TCAS coordination)
- TCAS processor
- Directional aerial on the top of the fuselage (for relative bearing measurement
- Omni-directional or directional aerial on the bottom of the fuselage
- Modified Vertical Speed Indicator
- Traffic Display
- Auditory and visual warning facilities

4.2 Modified Vertical Speed Indicator

The vertical speed indicator (VSI) is modified by the provision of eyebrow lights around the periphery. These lights are both red and green. Ranges of vertical speed to be avoided during an RA are coloured red and the target vertical speed green. The types of RA issued can initially be divided into two types, preventive and corrective. In the case of a preventive RA the system is telling the pilot that based on current vertical speed the intruder is not expected to be a threat but should the vertical speed be allowed to change to be within a certain range calculated by TCAS, a "close encounter" is expected. This range of vertical speeds is coloured red. In the case of a corrective RA, TCAS is telling the pilot that a change in vertical profile is necessary to avoid a close encounter. The target vertical speed required is coloured green and other ranges for which there would be a conflict are coloured red. The basic command is saying keep out of the red area and go for the green area if one is shown. The range given in green is normally quite small since over zealous increases in vertical speed will cause height deviations greater than necessary and may bring the aircraft into conflict with originally non-threatening traffic above or below. A diagram of a modified VSI is given at Figure 2, but in monochrome is not well depicted.

4.3 Traffic Display

The traffic display is normally located outside the primary field of view and can either be a dedicated display, shared with a suitable colour weather radar or integrated into a LCD VSI of standard format. Whatever the type of display the symbology is the same and a diagram of a typical display is given at Figure 3. Own aircraft is usually positioned in the lower part of the display and 3nm and 5nm range rings are provided. Traffic is shown at the range calculated by TCAS and at the relative bearing derived from the directional antenna. This is the only reason in the case of TCAS II for measuring relative bearing. Each target is annotated with its height difference from own aircraft in hundreds of feet with a + sign if above and - sign if below. If the intruder's vertical speed is greater than 500 feet per minute an upward or downward arrow is placed next to the relative height. There is also a facility for displaying the intruder's absolute flight level if required. To differentiate between aircraft with differing levels of threat, traffic of interest only (normally ±1200 ft and within 4 nm) is displayed as a solid white diamond, traffic currently generating a TA as a yellow sphere and traffic currently generating an RA as a solid red square. Some equipment provide the facility of showing all non-threatening traffic within 20nm and $\pm$7,000 ft of own aircraft as an outline white diamond. Intruders with Mode A transponders (ie. not giving height information) are also displayed but naturally without height information. Such aircraft cannot give rise to an RA but can generate a TA. TCAS assumes in this case that both aircraft are at the same altitude. A diagram of a typical Traffic Display is given in Figure 3. Again this monochrome version does not give the full effect but it is a useful guide.

4.4 Warning Systems

Two forms of Warning Systems are normally used in connection with TCAS. Visual warnings are in the form of annunciator lights on the glareshield (red for RA's, amber for TA's) and/or the central warning panel and also perhaps on the traffic display. Auditory warnings comprise a voice message designed to give a clear indication of the type of warning (TA or RA) and, in the case of an RA the nature (either preventive or corrective) and, if corrective, the action to be taken.

For example a TA is indicated by the word "TRAFFIC" repeated once.

A corrective RA uses a command word which indicates positive action eg.

CLIMB (repeated twice)

DESCEND (repeated twice)

REDUCE VERTICAL SPEED (repeated once)

A preventive RA involves the use of a word which indicates no action is necessary eg.

VERTICAL SPEED RESTRICTED
(repeated once)

MAINTAIN VERTICAL SPEED
(repeated once)

When TCAS deems the situation to be safe again the words "CLEAR OF CONFLICT" are enunciated once.

5. UK Inputs to Safety Studies

The UK has been involved in the work of the SSR Improvements and Collision Avoidance Systems Panel (SICASP), the ICAO Panel dealing with ACAS, for a number of years. The Panel has produced a set of Interim Standards and Recommended Practices (SARP's) on the basis of which equipment will be produced and procedures devised for the use of ACAS II. The SARP's are of an interim nature because until a significant number of ACAS II (effectively TCAS II) equipped aircraft have begun to operate, the implications to both flight deck and ATC operations cannot be fully assessed.

It has been necessary for UK workers to become very familiar with the details of TCAS, particularly the logic and the software designed to implement that logic. As a consequence of achieving this detailed understanding the UK (Civil Aviation Authority and Royal Signals and Radar Establishment) has, as part of its contribution to SICASP, carried out some unique analyses which have helped to provide some answers to the potential effects of ACAS and more importantly enabled estimates to be made of the <u>net</u> safety benefit of TCAS.

Recordings of secondary radar data using the latest monopulse equipment, were made of traffic operating in some sectors of UK airspace. These data were fed into a model which contained the ACAS II conflict detection and resolution logic and as a result all RA's, which would have been given, assuming all the aircraft in the recorded data were ACAS II equipped, were produced. Assuming that pilots would have reacted in accordance with the model's assumptions as regards reaction time, 0.25 g manoeuvre and a correct vertical speed, the aircraft trajectories following receipt of a resolution advisory could also be calculated.

This technique enables estimates to be made of alert rates, and also to identify situations where ACAS II might not give the required results. In particular, situations involving the high vertical speeds, of which some modern transport aircraft are capable, were seen in some cases to cause ACAS II to reduce separation and possibly induce an airmiss. This situation is demonstrated in Figure 4.. Based on the current flight trajectories, ACAS II calculates that own aircraft can provide the best vertical separation by an "altitude crossing manoeuvre". This type of manoeuvre results from the fact that the geometry of the current situation causes ACAS to command to an escape manoeuvre in which "own aircraft " crosses the projected altitude of the threat aircraft in order to maximise vertical separation. In Figure 4 it can be seen that after the RA is issued, the threat aircraft levels out (a common situation in terminal areas), leaving own aircraft climbing towards the threat. Again it must be stressed that TCAS has no knowledge of the future intent of either own aircraft or the intruder. This situation had been appreciated but was thought to be an uncommon event. Analysis of UK radar data showed that this was not the case and its frequency would be such as to reduce the net safety benefit of ACAS II very considerably. The logic was therefore modified to allow ACAS to recognise this situation and allow changes to the direction of the advisory after issuing an RA, delays in issuing the advisory and bias in the logic against crossing the projected attitude of the intruder. The flight trajectories using the modified logic are shown in Figure 5.

Also introduced at this stage was the modified definition of the warning time, devised by Bramson and referred to in 3.1.

6. UK Operational Trial of TCAS II

6.1 Objectives

Knowing that there was impending legislation mandating the carriage of TCAS II in US airspace, it became evident that UK aircraft would need to fit TCAS and that TCAS equipped aircraft of many nationalities would begin to appear in UK airspace. The UK CAA therefore decided that first hand experience of the use of TCAS II on a UK registered transport aircraft operating in UK (and European) airspace was necessary in order to complement similar trials in the USA. It was decided to take advantage of an offer of a loan of prototype equipment from a US manufacturer (Allied Bendix) under the auspices of the FAA. The equipment was fitted to a British Airways Boeing 737-200 aircraft operating on normal scheduled services in the UK and Western Europe. There were three basic objectives:-

- To assess of the effect of TCAS II on UK flight operations
- To enable UK aircrew to see TCAS II in operation
- Assess the effect of TCAS II on the UK ATC System

The trial was planned to take place in three phases:-

(1) Operation with TCAS II simply recording data with no display of information to the crew.

(2) Certification flight trials using a dedicated intruder aircraft in airspace away from all other aircraft.

(3) Operations with TCAS II being used on normal scheduled services by line crews.

6.2 Recording Phase

The first phase lasted from January 1989 to October 1989 and TCAS performance data from about 430 flying hours were obtained. Concurrent with these flights ground radar recordings were made when the aircraft was in the radar cover of a suitable UK ground station. The purpose of taking recordings both on the ground and in the air was to find out whether or not radar recordings used for the safety analyses described in section 5, gave the same information as that which would have been seen in the air. Estimates, based on radar studies of alert rates and of TCAS II performance in UK airspace formed one of the bases on which it was agreed that the trial was feasible. It was necessary to use airborne data to validate these estimates before crews would be allowed to use TCAS II on scheduled flights.

In fact the recorded data indicated that TCAS II would in many ways be less disruptive than predicted and yet validated the use of radar recordings.

Only four resolution advisories were detected from the recorded data which gave rate of about one per 100 hours. This was very much less than the value of one per 20 hours recorded in US trials and less than the one in 50-60 hours in UK airspace estimated from radar analysis. These were two reasons for the differences. First, the US data was based on operations in US airspace which is organised differently from UK and European airspace in that in Europe, public transport aircraft are largely separated from general and private aviation in all weather conditions whereas in the USA they are mixed together in good weather. Second, the TCAS II equipment used in the UK trial had the modified logic referred to at the end of section 6, whereas the US trials used the earlier logic. The radar analysis to date was also based on that same logic. Subsequent radar analysis of data using the modified logic gave similar rates to that obtained in the air. Of the four RA's recorded, two, both in the UK, were of the preventive type and the other two were of the corrective type although one of these was of very short duration (about 5 seconds). This small number of RA's did not produce sufficient data to enable a statistically significant comparison of rates derived from ground and air. The TCAS recorder only produced data on RA's and TA's and therefore it was necessary to compare data on the more frequent TA over the 430 hours.

A total 203 TA's were recorded in the first phase giving a rate of about 1 per 2 hours, very similar to that in the USA. TA counts had not previously been made using UK radar recordings for reasons given below and therefore no comparison could be made. By processing the ground radar data recorded at the time of the TA a comparison of air and ground derived data could be made. In fact in general the results were very close and the use of ground radar for predicting TCAS II advisories was validated. The two RA's generated in UK airspace were also found by analysis of radar data.

The TA rate was not originally examined by UK workers since the aim of the original radar analyses was to support safety studies. Since it is inherent in the design of TCAS II that no action be taken based solely on TA information, the TA rate had no safety implications. From the human factors point of view however the TA is quite important. It gives an indication that an RA may be imminent but as can be seen from the relative occurrences of RA's and TA's the probability of an RA following a TA is about one in fifty. It therefore has the potential to be disruptive to the crew activity, especially since further analysis showed that the TA is a much more likely event in terminal areas where crew workload is high, In addition, although crew were asked not to contact ATC in receipt of a TA, it is only human nature to show some concern on receipt of such a warning and perhaps ask ATC of the intention of an aircraft producing it. This gives rise to the possibility of increased RT activity at a time when the controller may already be busy.

Finally it was observed that one third of TA's were generated by aircraft with only a Mode A Transponder and therefore, although it would be shown on the traffic display, no height information would be given. This was definitely a potential source of crew concern and extra radio communications.

It was planned to examine the effect of TA's further in the final phase of the trial. Both aircrew and controllers were briefed to comment on the effect of the TA.

6.3 Certification flight trials

As part of the certification procedure to allow TCAS II to be used by crews on scheduled services, it was necessary to demonstrate that TCAS II performs in the manner specified and to assess the visual and auditory displays in encounter situations. Since it was unlikely (hopefully) that encounters would occur in normal scheduled operations, it was necessary to produce suitable scenarios in a controlled and safe manner. Because of the detailed knowledge of the UK workers it was possible to generate a set of flight tests to evaluate the performance of TCAS II against the manufacturer's specifications. The CAA BAe 125 executive jet aircraft was used as an intruder and a series of encounters flown under the control of RAE Aberporth in Wales. RAE Aberporth has a set of very accurate lock-follow radars which enable each aircraft to fly the very precise pre-computed tracks necessary to generate the appropriate TCAS advisories. The aircraft could be flown on trajectories with relatively small miss-distances (2000 ft laterally and 300 ft vertically) at both high closing speeds (up to 800 knots) and at high relative vertical speeds (up to 3000 feet per minute) in safety.

The BA B737 was flown by two test pilots one from BA and one from CAA with observers on-board to make relevant notes. The BAe 125 was crewed by two CAA pilots and a CAA observer. The full set of 15 scenarios took about four hours to complete. The trials were carried out three times altogether. The first set were successful in that the expected alerts were generated but a recorder fault prevented the logging of airborne data. The second set showed up interface faults between the TCAS processor and a newly developed Vertical Speed Indicator. The third set was a shortened version of the second set to demonstrate that the interface faults had been corrected. Ground radar recordings were made during these trials and the results compared with airborne data where available. Again the technique of predicting TCAS II performance using ground radar was validated in terms of predicting RA's but additionally it was shown that the reaction of the pilot, admittedly under test conditions, compared well with the assumptions made. It was also shown that escape manoeuvres do not need to be violent to achieve the required vertical rate.

6.4 Line Operations

It was unfortunate that at a late stage in the trials it became evident that for a variety of reasons the prototype equipment used could not be certificated for public transport operation.

The equipment used, although very similar to that used in a US trial in 1988/9 and certificated for US public transport, contained the up dated version of the software. This updated software was originally envisaged to be the final version which would be submitted to the FAA for certification. In the event further updates to the software planned for final production equipment were made. These updates were not incorporated into the equipment used for the UK trial - it would not have been possible in the timescale and their nature would not have affected the objectives. It did mean however that the FAA did not certificate the software contained in the prototype equipment used for the UK trial. The UK CAA were not in a position to carry out its own software certification although it had cleared the hardware installation and was satisfied by the certification trials.

It was however possible to do a limited number of public transport flights with the equipment showing TA's only. However again events overtook the trial. The manufacturers were no longer able to support the prototype equipment since they were addressing the problem of satisfying the large demand for production units to meet the timescale required by US legislation. The trial was therefore terminated with little crew or ATC experience. It must be stressed that the certification problems experienced with the prototype equipment are not expected in the case of production equipment.

6.5 Conclusions from the trial

Although the final stage of the trial was not reached the trial was of considerable benefit to both the CAA and British Airways. In the case of the CAA the technique of performing analyses of ground radar data to assess the likely effects of TCAS II when it becomes common has shown to be a valid predictive method.

Furthermore many of the certification problems likely to be encountered are now known and the procedures in the case of UK airlines can more quickly be developed.

British Airways have now had experience in installing TCAS II and no doubt will be able to fit their long-haul flights more efficiently based on this experience. Although crew operation of TCAS II was minimal, British Airways have now devised operating procedures and training material which will prove useful in the long term.

Finally the UK will be able to provide experience for the forthcoming European evaluation of TCAS II which will involve all current TCAS II manufacturers, several European airlines and most European ATC authorities. The current message from the UK is - do not underestimate the magnitude of the task.

7. The Future

7.1 Interaction of TCAS with ATC

The inability to proceed to the full operation use of TCAS during the UK trial prevented the examination of one of the more important aspects of TCAS ie its effect on the ATC system. As it happened the number of RA's recorded during the first phase suggest that, had the final phase proceeded, very little information in this area would have been obtained. As TCAS II becomes more common this effect will become more evident and its assessment is one of the major objectives of the forthcoming world-wide evaluation of which the European element mentioned in section 6.5 is a part. It must be stressed again that although TCAS II will give a warning if a collision or near miss is imminent, because of its limitations it will sometimes also give a warning when there is no risk. Indeed at high closing speeds a corrective RA can be issued when the lateral separation does not fall below 3nm. (this was demonstrated during the Aberporth trials). TCAS II therefore has the potential to cause aircraft to deviate from their cleared flight profiles during normal operations causing some disruption to ATC. Coupled with the potential increase in RT activity caused by TA's, the ATC authorities are naturally concerned. The true extent of the total effect on ATC will only become evident as more aircraft become fitted, but the results of the UK trial suggest that it will not become as serious as first anticipated.

A more serious problem is the situation where a pilot receives commands from TCAS and instructions from ATC which may be different and perhaps totally contradictory. The advent of ground based Conflict Alert systems may accentuate the situation. Ground-based Conflict Alerts are derived from radar data but do not use the same algorithms as TCAS and look ahead about 1-2 minutes, rather than 20-30 seconds as in the case with TCAS II. The UK is devoting considerable effort to the development of Conflict Alert and at the same time looking at its potential interaction with TCAS.

7.2 Further uses of TCAS II

The TCAS trials in the USA indicated that apart from the collision avoidance facilities provided, the traffic display was very popular with aircrew, particularly when ranges up to 20nm and height bands up to 7000 feet away from own aircraft were provided. TCAS was never envisaged to be an ATC in the sky and for many reasons cannot be so. There are however suggestions emerging from the USA, for using TCAS II for three further functions.

- Enable pilots to set up their own separation in trail on final approach.
- Reduce lateral separation on the North Atlantic Track System.
- Enabling staggered parallel approaches to be conducted in IMC in the case of closely separated runways.

The UK has serious reservations about the first two suggestions in the case of UK airspace, for the following reasons.

(a) Separations between aircraft on final approach are determined by the air traffic controller and are based on many factors most of which will be unknown to the pilot.

(b) UK workers on TCAS do not believe that the TCAS surveillance system is suitable for safely reducing North Atlantic Separation Standards. It was never designed for this task.

There are no parallel runways in the UK close enough to be relevant to the third suggestion.

8 Conclusions

The UK has been closely connected with TCAS for many years and has developed its own expertise, based on which it has been able to make positive inputs to its development. It is able to contribute to the international debate on TCAS from a position of knowledge based upon its own work and will continue to do so. TCAS is a unique system in that it directly involves both ATC and air operations and therefore must be progressed carefully to produce the desired safety benefits without unnecessarily detracting from the orderly and expeditious handling of traffic by ATC.

It is not possible to cover all aspects of TCAS II in any detail in this paper but Ref 3 gives more detail from both the UK and International point of view.

References

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3. Royal Aeronautical Society - Proceedings of Conference "The Traffic Alert and Collision Avoidance System (TCAS) - Its Development, Testing, Installation and Operational Use" - 4 January 1990.

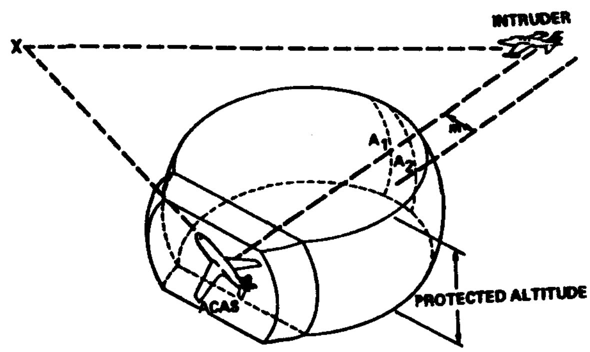
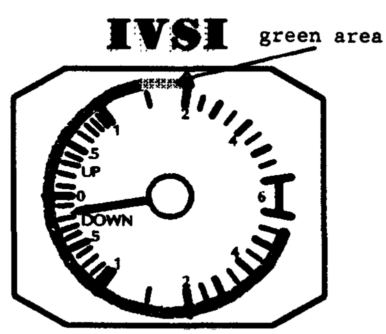
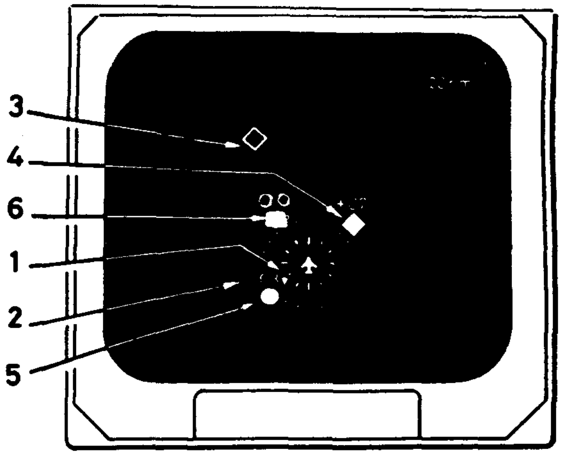


Figure 1 - TCAS II protection volume for two aircraft in level flight on collison courses



Area from + 1500 to - 6000 coloured red

Figure 2 - Modified IVSI



Legend

1. 3nm range ring
2. Relative altitude of traget (100's of feet) and vertical direction
3. Mode A target of interest (white)
4. Mode C target of interest (white)
5. Target generating TA (yellow)
6. Target generating RA (red)

Figure 3 - Traffic Display

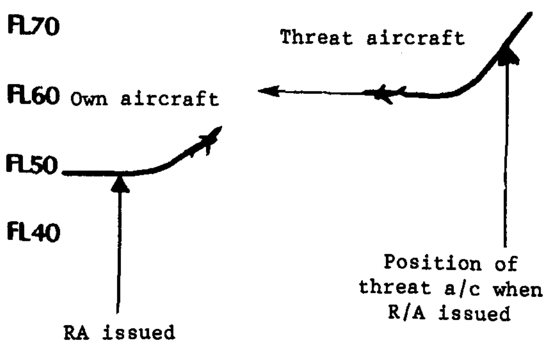


Figure 4 - RA resulting in reduced separation - original TCAS logic

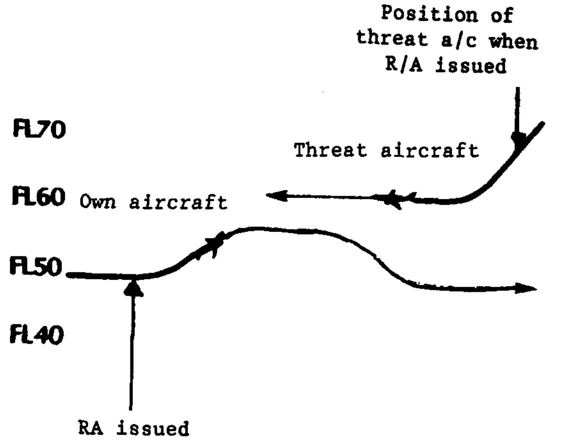


Figure 5 - RA involving sense reversal when threat aircraft levels out - later TCAS logic