

# Airborne Collision Avoidance System

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## Abstract

The paper provides an overview of the development and operational deployment of the Traffic alert Collision Avoidance system (TCAS). TCAS was one of the first software based “safety of life” systems deployed in aircraft.

Keywords: ACAS, TCAS, Lake Constance, Launceston.

## 1 Background

### 1.1 Introduction

TCAS is a “last ditch” aircraft collision avoidance system. In many parts of the world, aircraft with more than 19 passenger seats or greater than 15,000Kg maximum takeoff weight are required to be equipped with TCAS. TCAS is (quietly) credited with a number of airframe “saves” worldwide. Many airlines voluntarily equip with TCAS. Insurance companies recognise the value of TCAS as demonstrated by the lower insurance premiums for equipped aircraft.

### 1.2 Air Traffic Separation Concept

Aircraft collision avoidance is based on Structured Routes, Altitude Separation, Rules of the Air, Air Traffic Control (ATC); both Procedural and Radar, as well as “See and Be Seen”.

Aviation has built its enviable safety record using a layered approach. Every layer has a failure rate; however, with sufficient layers the probability of all layers being breached simultaneously can be extremely low.

### 1.3 The Need

The catastrophic collision in 1956 between two commercial airliners over the Grand Canyon (USA) spurred the first concerted effort to develop a collision avoidance system (CAS) for aircraft, to provide an additional safety layer. Until the late 1980s, technology

was not able to deliver a practical, effective and price viable CAS device for widespread fitment.

### 1.4 Early CAS Activity

A small number of Collision Avoidance Systems were proposed between 1971 and 1975. Each proposal had severe limitations including the requirement for dedicated equipment to be installed on each aircraft to be protected or avoided before any benefit was realised.

It was observed that a CAS which interrogated the ATC transponders that were already installed on all commercial and military aircraft and most private aircraft, would bring immediate benefit to CAS equipped aircraft; completion of fitment of CAS to all aircraft was not required. This was known as the Beacon-based Collision Avoidance System (BCAS). However, difficulties were encountered with the amount of RF generated in areas of high aircraft density.

### 1.5 TCAS Emerges

In response to a law enacted by Congress, in 1981 the USA Federal Aviation Administration (FAA) focussed development on an enhanced version of BCAS which became known as the Traffic Alert and Collision Avoidance System (TCAS). The FAA assumed responsibility for the necessary research, prototype development, demonstration of technical and operational feasibility, generation of standards and certification of TCAS equipped aircraft.

## 2 TCAS

### 2.1 The Functional Requirement

TCAS is a system of last resort and hence should have the following characteristics:

- Should only intervene when all “normal” means of separation have failed
- Should not be disruptive to “normal” separation means
- Should have minimum reliance on other systems
- Should work anywhere – even remote or oceanic areas
- Should ensure complementary manoeuvres are employed by the aircraft in conflict
- Should have a very high probability of successful conflict resolution.

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## 2.2 Consequences of the Requirements

Should only intervene when all “normal” means of separation have failed ...

There are many means of separation used by Air Traffic Control and Pilots. It is not practical for TCAS to be aware of all the various methods; new methods may develop over time. However, another way of approaching this requirement is to delay any corrective action as late as possible. That is, until there is time for only one more manoeuvre to resolve the conflict.

Should not be disruptive to “normal” separation means ...

The means of resolving the conflict must have a very low probability of generating another conflict; to avoid any domino events. Collision avoidance manoeuvres due to false alarms could be disruptive to normal ATC operations and need to be avoided.

Should have minimum reliance on other systems ...

The fact that a last ditch collision avoidance system must take action indicates that the “normal” means of separation, including systems, has failed, thus it would be wise to minimise any reliance on elements of possibly failed systems.

Should work anywhere – even remote or oceanic ...

This requirement implies that the system must be self contained in the aircraft and not reliant on ground system support; which could not be readily provided in remote and oceanic areas.

Should ensure complementary manoeuvres are employed by the aircraft in conflict ...

Some means is required to ensure that the two or more aircraft in conflict will choose complementary manoeuvres to resolve the conflict. This implies some form of communication between the CAS systems of the aircraft in conflict.

Should have a very highest probability of successful conflict resolution ...

## 2.3 TCAS - Basis of Operation

TCAS provides “last ditch” collision avoidance by detecting and tracking aircraft proximate to own aircraft. The relative movement of threat aircraft to own aircraft is assessed.

TCAS generates a Traffic Alert (TA) for aircraft which are predicted to come unhealthily close approximately 45 seconds before Closest Point of Approach (CPA). The TA draws the flight crew’s attention to the situation and assists their visual acquisition of the threat aircraft.

If the situation continues to deteriorate, at about 30 seconds before CPA, TCAS issues a Resolution Advisory (RA). Resolution is always in the vertical plane. The RA may be passive (don’t climb, don’t descend) or active (climb, descend). TCAS communicates the RA to other TCAS equipped aircraft to ensure complementary manoeuvres. The flight crew are expected to enact the RA

without delay. If followed correctly, the RA can be expected to cause a vertical separation between the aircraft of 300 to 800 feet. TCAS continues to reassess the geometry once per second and if required will vary the RA (increase climb, adjust vertical speed).

When the threat has passed, TCAS removes the RA and advises “Clear of Conflict”. The flight crew should return the aircraft to the ATC assigned level.

The manoeuvre is usually sufficiently gentle that for most passengers it goes unnoticed.

TCAS comprises a number of functions; surveillance, collision avoidance, crew alerting and co-ordination with other TCAS units. TCAS is implemented as an extension of the aircraft ATC Transponder installation.

### 2.3.1 System Components

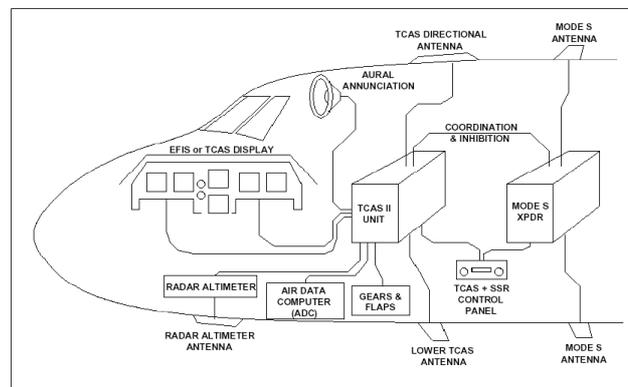


Figure 1: TCAS Block Diagram

### 2.3.2 Surveillance

Primary Surveillance Radar (PSR) was first used to support ATC in the late 1940s. PSR displays to the controller the plan view position of aircraft, however it does not know the Identity or Altitude of aircraft. Secondary Surveillance Radar (SSR) interacts with a Transponder carried on each aircraft. SSR interrogates the transponder to downlink Identity (Mode A) and Altitude (Mode C) information or more comprehensive data including Identity and Altitude (Mode S).

TCAS is a mini, on aircraft, SSR. It is perpetually scanning the sky around own aircraft searching for proximate aircraft. To ensure sufficient time for avoidance action in a high speed head to head encounter, TCAS has a minimum surveillance range of 14 Nautical Miles (NM), although typical units has a 40 NM range and the most modern units as much as 100NM range. Top and bottom antennas are used to ensure threat aircraft above and below are detected. The static, electronically steered antennas used to measure the position of proximate aircraft with a range accuracy of 1/125NM and a bearing accuracy of 3 degrees. These antennas are a mere 280mm long, 115mm wide and 25.4 high and operate in temperatures between -60° C and 100° C



at air speeds up to 600 knots.

Initial acquisition of a Mode S Transponder equipped aircraft is facilitated by the Mode S acquisition squitter; a spontaneous transmission including the aircraft's (worldwide unique) address. TCAS, upon reception of acquisition squitter, adds the new aircraft to the track table and uses Mode S selective interrogations to measure range and bearing and extract other aircraft's altitude.

**Figure 2:**  
**Honeywell ANT-81A**

Mode A/C Transponder aircraft are also detected by TCAS. TCAS is constantly interrogating Mode C (Altitude). Transponders in proximate aircraft respond with Altitude information. Mode C interrogations are not selective and simultaneous overlapping replies may be received from aircraft at similar range. TCAS uses both directional interrogation and variable interrogation power (whisper / shout) to selectively extract a response from each transponder. Whisper / shout relies on the statistical variation of receiver sensitivity between individual transponders.

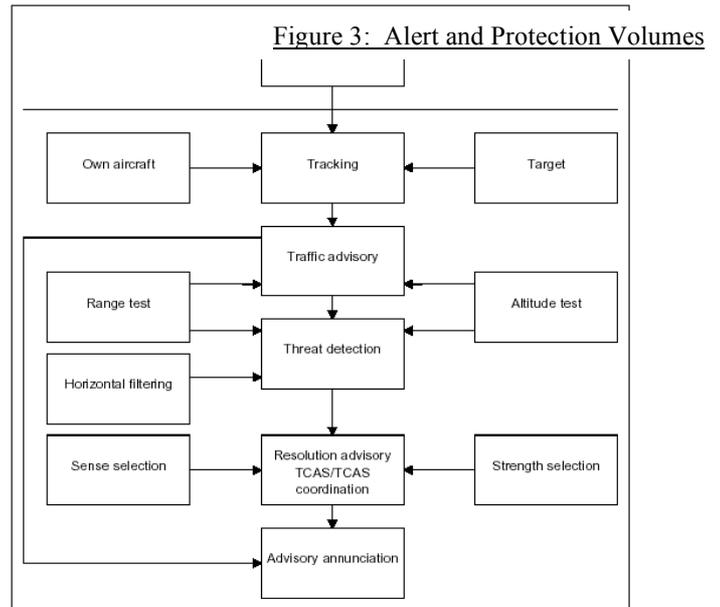
TCAS periodically interrogates each aircraft recorded in the track table. The range is determined from the time elapsed between interrogation and reply, bearing is determined by the directional antenna and altitude is received in the reply from the other aircraft's altitude encoder. The rate of change of range, bearing and altitude are estimated from successive interrogations.

It can be seen that TCAS will not detect aircraft which do not have a functioning Mode A/C or Mode S transponder. Similarly, TCAS can not determine the relative altitude of a proximate aircraft if it is not transmitting altitude data.

### 2.3.3 Collision Avoidance Logic

The aircraft surveillance data is passed to the Collision Avoidance Logic. The relative geometry and closure rate between own and each proximate aircraft is assessed once per second.

Each TCAS equipped aircraft independently makes its own assessment of the encounter geometry. If TCAS determines that a proximate aircraft may be a threat, a TA is generated and annunciated to the crew. If TCAS determines that a Resolution Advisory is required; the RA is annunciated to the crew and broadcast to the threat aircraft. TCAS on the threat aircraft (if fitted) is required to select a complementary RA.



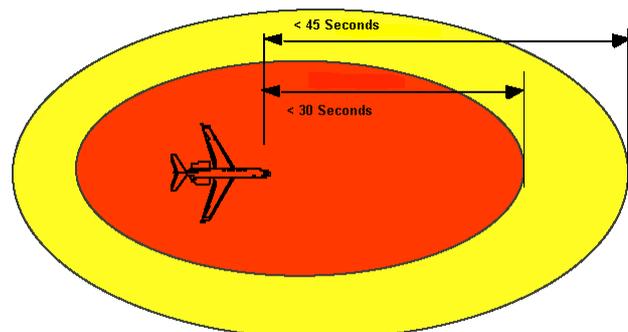
In a symmetrical encounter, there is a small period of time in which the TCAS units in two aircraft could generate conflicting RAs. A simple tie break is used to resolve this possibility; the aircraft with the lower value unique address maintains its RA and the aircraft with the higher address must choose a complementary manoeuvre; even if this requires a reversal of its RA.

TCAS is capable of managing multiple, simultaneous threats.

#### 2.3.3.1 Distance versus Time

Traditionally, separation of aircraft is based on distance (eg 5 NM). However, it can easily be seen that for two high speed aircraft 5NM apart flying head to head there is little time to resolve the situation. In contrast, the same two aircraft 2 NM apart in trail, provided the speed is the same, will not collide. Time to Closest Point of Approach (CPA) is the essence and hence TCAS computes and assesses in time not distance.

TCAS typically provides warning of proximate traffic some 45 seconds before CPA. If the situation deteriorates, at some 30 seconds before CPA, the Resolution Advisory is issued. This is just sufficient time for one escape manoeuvre to be enacted and become effective.



## 2.4 Avoidance Manoeuvre

Avoidance of a collision could be achieved by change of speed, change in course or change of altitude. Adequate separation in horizontal plane would be half to one nautical mile. Adequate separation in the vertical plane would be 300 to 500 feet. It can be seen that the time required to achieve vertical separation is much less than that to achieve horizontal separation. Hence the use of a vertical manoeuvre allows the intervention of TCAS to be much later than if a turn was used; tens of seconds versus hundreds of seconds.

The required avoidance manoeuvre is communicated to the pilot as a Resolution Advisory (RA). The RA may be passive (don't climb / don't descend) or active (climb / descend / adjust vertical speed).

As the encounter progresses, TCAS re-assesses the geometry of the encounter and usually softens the Resolution Advisory as the desired vertical separation is established.

In rare circumstances, TCAS can reverse the sense of the Resolution Advisory; having previously issued a Climb Advisory, the reversal would be "Descend, Now Descend".

To ensure the Resolution Advisory (RA) does not direct the aircraft into the ground, input is taken from the Radio Altimeter and Descent RAs are not issued when close to the ground.

Similarly, the aircraft capabilities are known to TCAS to avoid issuing impossible RAs such as "climb" when the aircraft is already at maximum altitude.

## 2.5 Human Machine Interface (HMI)

There are three main elements of the Human Machine Interface (HMI):

- Plan Position Display of traffic and threat aircraft;
- Aural Prompts for the required action and
- Display of Required Avoidance Manoeuvre.

### 2.5.1 Plan Position Display

The Plan Position Display depicts to the pilot the position of proximate and threat aircraft, relative to own aircraft; the position relative to the ground is of no interest. The colour of the aircraft symbols is used to distinguish the priority. White is used for aircraft of no specific interest and for proximate aircraft for which TCAS has generated a Traffic Alert. Red is used for threat aircraft for which TCAS has generated a Resolution Advisory. Yellow is used to indicate aircraft which were a threat but the threat has passed. Beside each symbol is a number indicating the other aircraft altitude relative to own aircraft in the unit of 100 feet, together with indication of other aircraft climb or descent.

The prime purpose of the Plan Position Display is to give the pilot situational awareness and as an aid to visual acquisition of threat aircraft. The Plan Position Display is

not intended to be the basis for a pilot initiated avoidance manoeuvre.

The TCAS Plan Position Display is usually implemented in the Instantaneous Vertical Speed Indicator (older cockpits), shared display with the weather radar (older aircraft) or shared on a multipurpose display (modern glass cockpit aircraft).

Figure 5: IVSI Manoeuvre Display

### 2.5.2 Aural Prompts

Aural prompts are the prime means of alerting the pilots to a threat and the required action to avoid the threat aircraft.

The initial aural alert for proximate traffic is "Traffic, Traffic"; the pilot, by reference to the Plan Position Display, determines the relative position of the proximate aircraft and attempts visual acquisition and prepares for possible avoidance action.

Should the situation deteriorate and the other aircraft becomes a threat, the Resolution Advisory is aurally announced; "Climb, Climb, Climb". This, together with the display of the avoidance manoeuvre prompts the pilot to initiate the avoidance action.

As the encounter progresses any change to the required avoidance action generates further aural prompts such as the strengthening advisory "Increase Descend", the softening advisory "Adjust Vertical Speed" or, in rare circumstances a reversal, "Descend, Now Descend".

In designing systems, cultural differences need to be considered. Extensive research trials with airline pilots in flight simulators disclosed that pilots with a western background responded most reliably to a slightly higher than average pitch female voice. However, pilots of some other cultural backgrounds largely ignored the female voice and the use of an authoritative male voice is more effective.

### 2.5.3 Display of Avoidance Manoeuvre

TCAS Avoidance Manoeuvre is always in the vertical plane. The presentation of the required manoeuvre is in the form of required / forbidden vertical speed or the required / forbidden aircraft pitch; which will achieve the required and prevent the forbidden vertical speed.

In aircraft with standalone Instantaneous Vertical Speed Indicators (typically older aircraft), segments of the arc are lit in Red and Green to indicate represent the forbidden range and recommended vertical rate respectively.

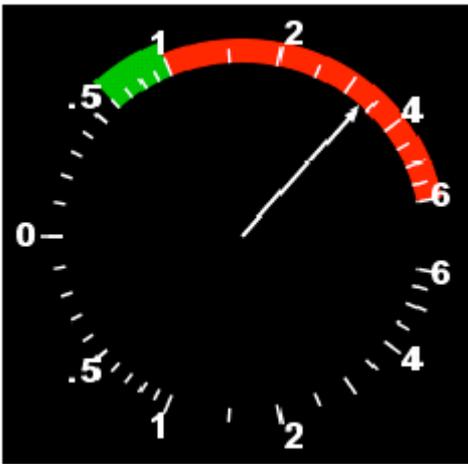


Figure 7: Flight Director Manoeuvre Display

Alternatively, the forbidden pitch for the aircraft may be displayed as a red trapezoid on the Flight Director (FD) (see figure 7 above) to provide a very simple and intuitive means of indicating the required aircraft pitch and consequent vertical speed. In the instrument above, the aircraft pitch, represented by the small black square in the middle, is within the forbidden zone and a descent is required. The pilot simply pushes the nose down until the square is just outside the red trapezoid.

The Instantaneous Vertical Speed Indicator (IVSI) (Figure 5 above) shows the aircraft is climbing at 3,300ft/min, the range of forbidden vertical speed is 1,000 to 6,000ft/min and recommended vertical speed is between 600 and 1,000ft/min.

The pilot of this aircraft needs to act now!

In modern “glass” cockpits the vertical speed information is may be displayed as a vertical speed tape (figure 6 below - left) or as a graphical mimic of the Instantaneous Vertical Speed Indicator (figure 6 below – right).

The colours Red and Green are again used to represent the forbidden range and the recommended vertical speed.

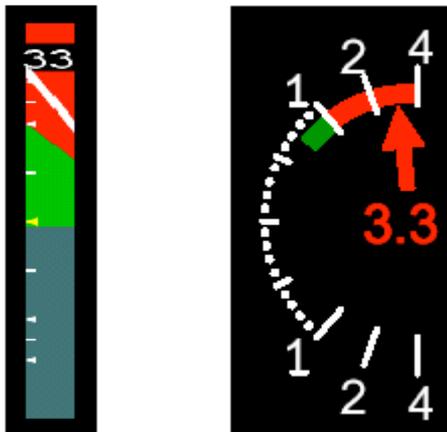


Figure 6: Manoeuvre Display in Glass Cockpit

### 2.5.4 Expected Pilot Response to TA & RA

In response to a Traffic Advisory, the Pilot is expected to attempt visual acquisition and prepare for any Resolution Advisory.

In response to a Resolution Advisory, the Pilot is expected to recognise and enact the RA within 5 seconds. Response to any further RA is expected to be enacted within 2.5 seconds.

There is no time to ponder the wisdom of an RA! This requires a very high degree of trust in TCAS.

Pilots are generally trained to obey ATC, however in the specific case of TCAS RA and ATC instruction being in conflict, the RA must take priority.

Considerable initial training and periodic refresher training is required to ensure that pilots, on the infrequent occasions that an RA is generated, respond correctly and in a timely manner.

### 2.6 An Encounter – The Pilot’s View

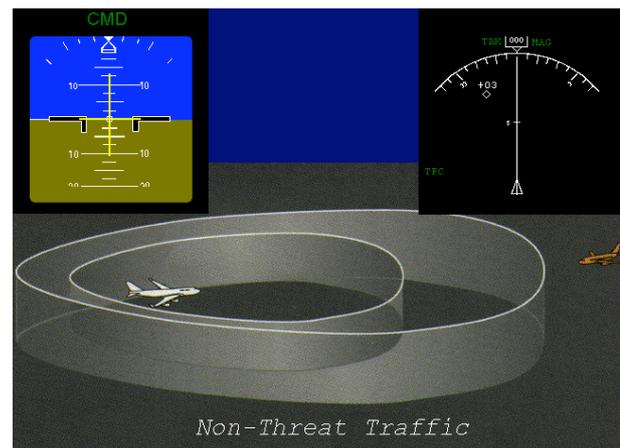
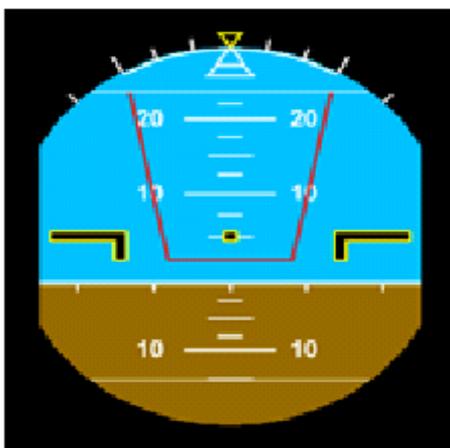
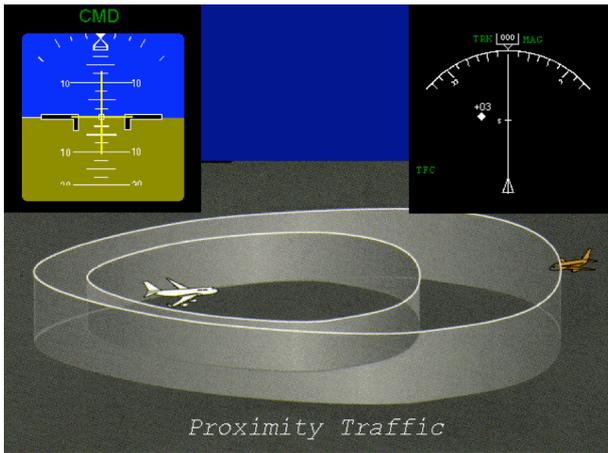


Figure 8: Non-Threat Traffic

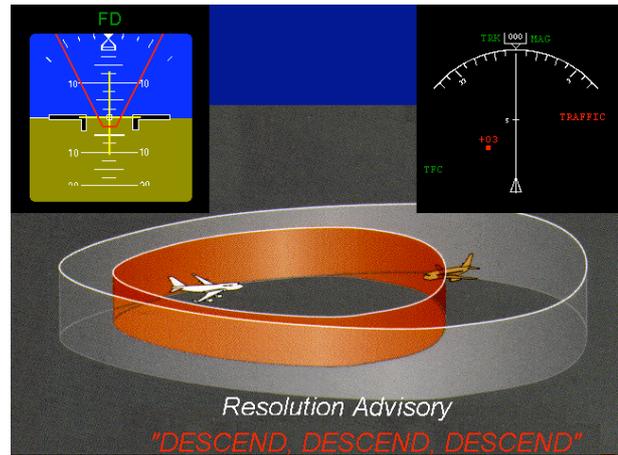
Non-threat Traffic (see figure 8 above) is shown with an un-filled white diamond in relative position to own aircraft on the TCAS display. Relative altitude is displayed next to the traffic; in this case the traffic is 300 ft higher than own aircraft and level.





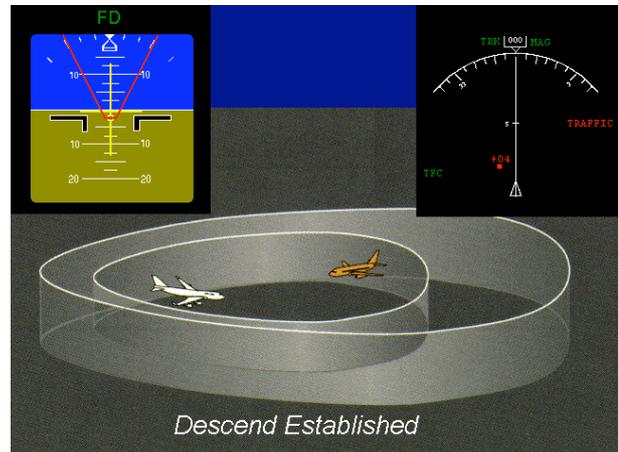
**Figure 9: Proximity Traffic**

Proximity Traffic (see figure 9 above) is displayed similarly to non-threat traffic but with the diamond is now filled. The aural warning “Traffic, Traffic” is announced.



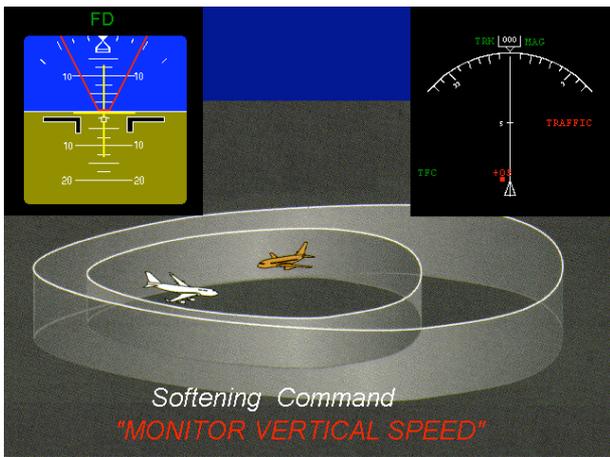
**Figure 10: Resolution Advisory**

The symbol of the threat traffic (see figure 10 above) changes from a white diamond to a filled red square. The aural advisory “Descend, Descend, Descend” is announced. A red trapezoid indicating forbidden aircraft pitch is displayed on the Flight Director. By changing the aircraft pitch to be outside the forbidden region, the required descent rate is achieved.



**Figure 11: Descend Established**

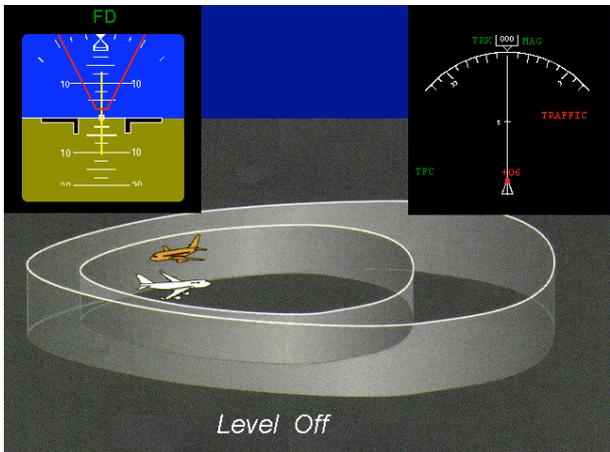
Figure 11 above shows that the pilot has initiated and established the required descent rate; indicated by the “nose” of the aircraft now pointing at the red trapezoid on the Flight Director.



**Figure 12: Softening Command**

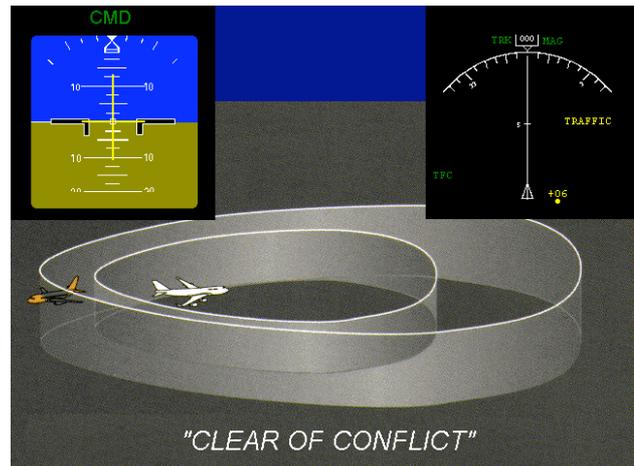
Figure 12 above, shows that the required vertical separation has been achieved, the descent can be arrested and new required aircraft pitch is displayed on the Flight Director. The aural prompt “Adjust Vertical Speed” is issued. The pilot adjusts the aircraft pitch to achieve the revised vertical speed.

Note: “Monitor Vertical Speed” was used in early versions of TCAS; in light of operational experience the phrase “Adjust Vertical Speed” was adopted in the current version of TCAS.



**Figure 13: Level Off**

Figure 13 above, shows that the descent has achieved the required vertical separation and own aircraft will pass safely below the threat aircraft. Own aircraft is now levelled off and the RA displayed precludes any climb.



**Figure 14: Clear of Conflict**

The two aircraft have passed and the distance between them is growing; figure 14 above shows that the conflict has finished. The threat aircraft symbol becomes yellow. The aural advisory “Clear of Conflict” is annunciated.

The restriction on vertical rate has been removed and the pilot will now initiate a climb to return the aircraft to the ATC assigned Flight Level.

## 2.7 International Standardisation

The Collision Avoidance System is required to work anywhere in the world and hence it is necessary that systems operate to agreed standards.

The International Civil Aviation Organisation, a body of the United Nations, publishes Standards and Recommended Practices (SARPS) for aviation systems including Secondary Surveillance Radar (SSR) and the Airborne Collision Avoidance System (ACAS). SARPS define the Signals in Space, the function, the inter-aircraft co-ordination and the expected pilot response.

TCAS is the only implementation of the ACAS standard.

RTCA (USA) and EuroCAE (Europe) produce Minimum Operating Performance Standards (MOPS) to define equipment performance.

ARINC (USA) produces Characteristics to standardise physical and electrical attributes of equipment so that systems from different manufacturers are interchangeable.

## 2.8 In Service Experience

### 2.8.1 Mandatory Reporting

TCAS was deployed across the USA Air Transport Fleet in a little over two years due to a law passed by Congress. To ensure that any significant operational consequences were captured early, mandatory reporting of TCAS encounters involving a Resolution Advisory was implemented; this approach was adopted in many countries; including Australia.

A free exchange of the experience between countries facilitated prompt recognition and resolution of operational issues.

## 2.8.2 Technical Recording

The generation of a RA is required to be recorded on an aircraft Flight Data Recorder.

While not mandatory, many TCAS installations include recording of the details of TCAS events. Analysis of the recordings of incidents and near misses involving TCAS have been greatly enhanced the knowledge of the behaviour of TCAS itself, the pilot's response and other technical issues. This facilitates prompt recognition and resolution of issues and promotes confidence and trust in the TCAS system.

Typically recording includes:

- Time,
- Own Altitude, Vertical Speed, Advisory and
- Intruder Range, Bearing, Vertical Speed and Resolution Advisory.

## 2.8.3 Legal Considerations

The Captain of an aircraft has the responsibility for the safety of aircraft. Initially, it was found that some pilots were reluctant to follow a TCAS Resolution Advisory without first visually checking or conferring with other members of the flight crew.

However, if TCAS is to work predicably and efficiently, it is necessary for the crew to respond promptly and fully with the Resolution Advisory issued by TCAS; there is no time to consider the wisdom of the RA.

To gain the required reliable and prompt response to a TCAS RA, ICAO recommends that the Captain is absolved of responsibility for collision avoidance while manoeuvring in compliance with a TCAS RA.

Similarly, ICAO recommends that, once an aircraft departs from its clearance in compliance with a RA, ATC is absolved of responsibility for separation between that aircraft and any other aircraft affected as direct consequence of the RA manoeuvre.

## 2.8.4 Installation Issues - Aircraft Address

Both Mode S SSR surveillance and the TCAS Collision Avoidance Logic required unique identification of aircraft. The Aircraft Address is a 24 bit number allocated uniquely worldwide and is used by SSR, TCAS and other aircraft systems such as communication networks and Emergency Locator Transmitters. Blocks of Addresses are allocated by ICAO to states (countries). States use various allocation schemes to ensure unique allocation.

In Australia, aircraft registration is in the form VH-xxx where xxx is three letters (ie VH-ABC). The Aircraft Address allocated is determined by a simple algorithm applied to the three registration letters. Thus given an aircraft Registration the Aircraft Address can be determined and vice versa.

There are a number of monitoring stations around the world where some characteristics of the transponder and TCAS installation are measured as aircraft fly past. One test is to compare the Aircraft Address read from the aircraft by radar to the Aircraft Address associated with

the Registration of the aircraft contained in the Flight Plan.

During the early years of Mode S and TCAS a considerable number of aircraft were found to have incorrect Aircraft Address. A concerted effort worldwide was required to ensure correct allocation and implementation of Aircraft Address.

## 2.8.5 Pilot Response to Softening RA

The TCAS softening RA is intended to alert the crew to a reduction in the required vertical rate after an RA when adequate vertical separation has been achieved. Pilots were expected to note the reduced vertical rate required on the visual display and reduce the aircraft vertical speed accordingly.

Early versions of TCAS used the aural prompt "Monitor Vertical Speed". In service it was found that many pilots indeed monitored the vertical speed but did not change it! This led to excessive changes in altitude and could potentially involve additional aircraft (domino effect).

The current version of TCAS (version 7.0) uses the aural advisory "Adjust Vertical Speed". The in-service effectiveness of this phrase remains under scrutiny.

## 2.8.6 Awkward Geometry – The Dallas Bump

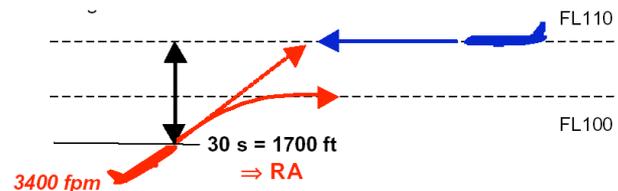


Figure 15: Dallas Bump Geometry

The above geometry is problematic for TCAS. The climbing aircraft, provided it levels at FL100, is not a threat to the aircraft at FL110; but will the level out occur? – normally yes. However, if for any reason the level out does not occur, there is insufficient time to recognise the lack of level off and take avoiding action. TCAS generates an RA which, usually is a nuisance but ensures collision is avoided. Typically, the lower aircraft is given a limit on climb rate and the upper aircraft receives a Climb RA; the bump.

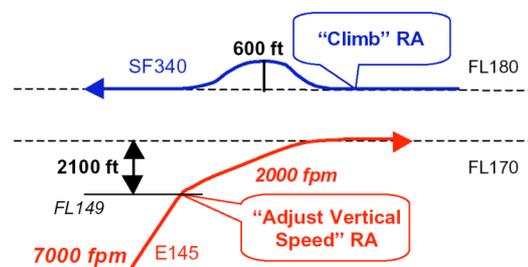


Figure 16: Dallas Bump Actual Occurrence

By reducing vertical speed to less than 1,000ft/min for the last 1,000ft before level off, TCAS has sufficient time to detect the level off and avoid an unnecessary RA.

### 2.8.7 Confusion of Functions

Since the introduction of TCAS innovative people have envisaged many applications of TCAS in addition to its collision avoidance function. The pilots of certain airlines were in the habit of using TCAS to “see” if there was anything behind its aircraft prior to pushing back from the terminal. It was soon (painfully) discovered that TCAS does not “see” ground service vehicles.

Trials using TCAS to determine in-trail distance from a lead aircraft prior to climbing/descending through the level of the lead aircraft have been conducted. While successful, concern was raised that TCAS does not provide positive identification of aircraft and incorrect identification could result in adequate separation from the wrong aircraft and possible inadequate separation from the right aircraft.

Great care must be exercised to ensure that as any new function is introduced, the new function does not detract from the original and prime function.

### 2.9 Performance Achieved

TCAS does not absolutely guarantee that two aircraft will not collide; the presence of TCAS results in a worthwhile reduction in the collision risk. Studies in the United Kingdom evaluated that the TCAS contribution to collision risk reduction is as follows:

Risk with TCAS = Risk without TCAS x Ratio  
( 0 = TCAS perfect, 1 = TCAS useless)

Own aircraft is TCAS equipped and:	Ratio
▪ Threat Aircraft equipped, RA obeyed, own RA obeyed	0.05
▪ Threat Aircraft not equipped, own RA obeyed	0.12
▪ Threat Aircraft equipped but RA ignored; own RA obeyed	0.25
▪ Threat Aircraft equipped/not equipped, own RA ignored	0.35

It can be seen that if both aircraft are equipped and RAs in BOTH aircraft are obeyed, a reduction in collision risk by a factor of 20 is achieved – quite substantial. If only own aircraft is equipped and the RA is obeyed, a reduction in collision risk by a factor of nearly 10 is achieved – worthwhile.

However, if the RA is ignored by either flight crew the protection offered by TCAS is greatly reduced. The protection afforded comes from one of the aircraft pair manoeuvring in response to TCAS.

Manoeuvring the aircraft in the opposite direction to the RA is likely to defeat TCAS and no protection can be expected.

### 3 Examples from Operational Use of TCAS

Over 20,000 aircraft worldwide are equipped with TCAS.

The Australian Transport Safety Board web site records 14 Investigations of serious aircraft encounters where TCAS issued Resolution Advisories for the seven year to May 2004. None involved collision.

The first two occurrences described below are most atypical and are chosen to illustrate specific points. The third occurrence is representative of many encounters.

The descriptions focus on the TCAS aspects of the encounter and should not be taken as a comprehensive account of the occurrence.

#### 3.1 TCAS Failure – Technical

On the 28th June 1999, British Airways flight BA027 passed in the opposite direction, Korean Air flight KE507 in Chinese airspace at the same level and approximately 200 meters lateral separation. Both aircraft were responding to TCAS Resolution Advisories (RA) at the time and no other aircraft are thought to have been involved.

The Korean Air aircraft was cruising at 31,500 ft and the British Airways aircraft at 33,500 feet when the Korean Air aircraft reportedly received a TCAS Climb RA for a threat shown at 400 feet below. The Korean Air aircraft followed these TCAS climb commands until the two aircraft crossed altitudes.

The British Airways crew reported having seen the Korean Air aircraft on TCAS 1900 feet below. The British Airways TCAS issued a Descend RA, with the Korean Air aircraft shown 400 feet below and climbing, approximately ten seconds before the aircraft passed. The separation was estimated from the British Airways First Officer's visual acquisition of the Korean aircraft through the side windows of the flight deck.

Why did the Korean Aircraft receive the apparently incorrect RA to climb?

Immediate testing of both aircraft following the incident revealed no obvious defects with the TCAS, transponders or Air Data Computers (altitude system). The Flight Data Recorder from the British Airways aircraft confirmed the RA generated on that aircraft but the Flight Data Recorder record from the Korean Air aircraft was not available. The aircraft were returned to service with a specific watch for TCAS, Transponder or Altitude abnormality. No abnormalities were noted on the British Airways aircraft but the Korean Air aircraft received one report from ATC of incorrect altitude received from the Transponder. The Air Data Computer #1, Transponder #1 and TCAS unit of the Korean Air aircraft were replaced and no further abnormality was observed.

British Airways, with assistance from Korean Air, undertook a persistent and comprehensive investigation to determine the cause of erroneous behaviour of TCAS.

Initially, many scenarios were considered but the focus soon settled on the possibility of an error in the own

aircraft altitude perceived by the TCAS unit on the Korean Air aircraft.

TCAS determines threat aircraft altitude by interrogating the transponder on the threat aircraft and requesting its altitude. Thus possible sources of error in threat aircraft altitude as perceived by TCAS include threat aircraft's Air Data Computer, transponder and associated wiring. Own aircraft altitude is received by TCAS via own aircraft's transponder from own aircraft's Air Data Computer. Any fault in this chain could be a source of error in own aircraft altitude as perceived by TCAS.

Early altitude encoders were mechanical devices integrated into the barometric altimeter. The electrical output was a 10 bit parallel bus. To ensure that only one bit of the bus changes on each transition (to ensure there are no transient false values generated as the output changes between successive values) the altitude is represented in Gray code, not binary code. This interface is known a "Gillham" interface.

With the British Airways aircraft at 33,500 ft and the Korean Air TCAS unit displaying the threat aircraft 400ft below, TCAS must have perceived own aircraft to be at 33,900ft, rather than the actual 31,500ft. The Gillham codes for 34,000ft and 31,500ft differ only in bit B1. Similarly, the Gillham codes of 33,900ft and 31,600ft also only differ in bit B1 and in the same sense. A 100ft change is the smallest increment of change in the Gillham system.

However, a failure in the Gillham altitude source or associated wiring had been foreseen by Transponder designers. To guard against this possibility the transponder has input from two altitude sources and performs a cross check. Significant difference between the two sources causes the transponder to consider the altitude invalid and altitude is not passed to TCAS. However, to support backward compatibility with early transponder installations, a pin in the aircraft's transponder connector must be connected to the common to enable the cross check. Absence of this connection would disable the cross check.

Korean Air examined the aircraft wiring and found no fault with the Gillham wiring to account for a false level on bit B1. The cross check enable pin, while present and correctly wired, was not correctly inserted into the connector body thus cross check was not operating.

Examination of the TCAS unit and Transponder #1 did not reveal any fault. However, testing of the Air Data Computer #1 revealed intermittent operation of Bit B1 of the Gillham interface. The fault was traced to a transistor in the shaft encoder; which had been manufactured in 1969. The transistor was tested at a specialist Integrated Circuit Engineering company and the failure was determined to be due to moisture ingress.

Thus the probable sequence of events was as follows.

The two aircraft were cruising at their assigned altitudes, the Gillham interface was working correctly and the British Airways crew observed on their TCAS the Korean Air 1,900 ft below.

Perchance, as the aircraft came closer, the intermittent transistor caused Bit B1 of the Gillham interface to feed incorrect altitude to the Transponder #1 of the Korean Air aircraft. Due to the incorrectly inserted pin in the aircraft's Transponder connector the comparison function was in-operative and the error in the altitude data was not detected.

The incorrect altitude code was passed to the TCAS unit which rejected the abrupt change in altitude; after the new value had settled for a short period of time it was accepted. The erroneous value represented an altitude 400ft higher than the British Airways aircraft and hence displayed the British Airways aircraft 400ft below.

As the aircraft came closer and longitudinal separation was lost, the Korean Air TCAS generated a Climb Resolution Advisory. During the Korean Air aircraft climb, the incorrect Bit B1 initially caused the sequence of altitude codes generated to falsely indicate descent.

After the aircraft had climbed through 32,800ft, where Bit B1 in Gillham code changes state, the altitude codes generated correctly reflected the Korean Air aircraft's altitude.

Meanwhile, the TCAS of the British Airways aircraft tracked the inconsistent sequence of altitude reports received from the Korean Air aircraft and due to low tracking confidence had not issued an Advisory.

After Korean Air aircraft passed 32,800ft, the correct codes lead to increased tracker confidence and a Resolution Advisory was issued. With the two aircraft now essentially co-level and having received the "Climb" Resolution Advisory broadcast from the Korean Air aircraft, the British Airways TCAS issued a complementary RA to the British Airways crew – "Descend".

Thus the two aircraft which were adequately separated by 2,000ft vertically were guided by TCAS through the same altitude when there was not adequate lateral or longitudinal separation.

### 3.1.1 Observations

This is the only known case of TCAS (and related) equipment failure causing a safely separated aircraft to be guided into a near miss.

To prevent a re-occurrence:

- Regulations now require functional test of the altitude cross check function;
- the used of Gillham code interfaces is discouraged and
- new aircraft use modern digital communications (not Gillham interfaces).

### 3.2 TCAS Failure – Human (Lake Constance)

On 1 July 2002, due to an unfortunate chain of events and while under Air Traffic Control (ATC), a Tupolev TU-154M passenger aircraft and Boeing 757-200 freighter were flying on courses that intersected at (roughly) right angles and at the same altitude.

Even though both aircraft were equipped with TCAS, they collided.



Figure 17: Map of Lake Constance Collision

The B757, crewed by a captain and a co-pilot, was flying level at FL360. The sequence of the TCAS encounter was:

- (21:34:30) The co-pilot, who had control of the aircraft, handed control to the captain and left his seat to visit the lavatory.
- (21:34:42) TCAS issued a Traffic Advisory drawing the captain's attention to an aircraft to his right and at the same level. The co-pilot promptly returned from the lavatory.
- (21:34:56) TCAS issued the Resolution Advisory (RA) "descend, descend".
- (21:34:58) Approximately 2 seconds later the autopilot was switched off, the control column pushed forward, the engine thrust reduced and descent at 1,500 ft/minute was established.
- (21:35:10) The co-pilot remarked "traffic right there"; the captain replied with "yes".
- (21:35:10) TCAS strengthened the RA; "increase descent, increase descent". By this time the co-pilot had regained his seat and put on his headset. His reaction to the advisory was "increase". The aircraft's rate of descent increased to 2,600 ft/min.
- (21:35:19) The crew reported "TCAS descent" to Zurich ATC.
- (21:35:26) The co-pilot repeated "descend" to the captain.
- (21:35:30) The co-pilot said "descend hard" to the captain.
- (21:35:32) The aircraft collided with the TU-154M at 34,890 ft.

The Tupolev crew comprised the commander (left seat and usually the pilot in command), instructor (right seat, most senior pilot and pilot in command on this flight), flight navigator, flight engineer and a further pilot (usually the co-pilot but on this flight he had no function).

The sequence of the TCAS encounter was:

- (21:34:42) TCAS issued a Traffic Advisory drawing the crew's attention to an aircraft to their left at the same level. Both the commander and the co-pilot called out "traffic, traffic".
- (21:34:49) Zurich ATC instructed the crew "descend flight level 350, expedite, I have crossing traffic"; the transmission took 8 seconds. During the transmission the instructor (pilot in command) requested the commander to descend.
- (21:34:56) the control column was pushed forward, the autopilot (vertical channel) switched off and descent commenced and became established at 1,500ft/min.
- At the same time (23:34:56) TCAS generated a RA "climb, climb".
- (21:34:59) The co-pilot queried "It (TCAS) says "climb"". The instructor (pilot in command) replied "He (ATC) is guiding us down". The co-pilot responded enquiringly with "descend?".
- (21:35:03) Zurich ATC interrupted the discussion with "descend level 350, expedite, descend". The instruction was acknowledged by the Instructor (pilot in command).
- Zurich ATC advised "Ya, ... we have traffic at your 2 o'clock now at 360"; the commander asked "where is it"; the co-pilot answered "here on the left side". The Navigator said "It is going to pass beneath us!".
- (21:35:05) The commander pushed the control column again and the rate of descent increased to 2,000 ft/min.
- (21:35:24) TCAS issued a strengthened RA "increase climb". The co-pilot commented "it says climb".
- (21:35:27) The control column was pulled and the thrust levers advanced a small amount.
- (21:35:31) The control column was pulled back abruptly and the thrust levers pushed full forward.
- (21:35:32) The aircraft collided with the Boeing 757 at 34,890 ft.

### 3.2.1 Observations

TCAS operated correctly and issued advisories which, if followed, could be expected to have averted the collision.

The Boeing 757 crew responded to the TCAS Traffic Alert and the two Resolution Advisory instructions promptly and in accordance with their training and TCAS philosophy.

However, on the Tupolev, when faced with the repeated, urgent ATC instructions which conflicted with the TCAS Resolution Advisories, the Instructor (pilot in command) decided to follow ATC instruction and ignored TCAS. The commander obeyed the pilot in command's requests. The co-pilot challenged the pilot in command's decision (twice) but the pilot in command re-affirmed the decision to descend. The Navigator also queried the decision but the decision was not changed.

It could be concluded that TCAS "failed" because the crew of the Tupolev had not been explicitly trained to obey TCAS even when TCAS Resolution Advisories are in contradiction to ATC instructions.

Indeed, the terms "resolution advisory" and ATC "instructions" do not convey the correct priority when they are in conflict.

It should also be noted that TCAS is not mandatory or generally fitted in Russian domestic aircraft and for the particular incident geometry; the Russian (but not the International or German) rules of the air required the Tupolev to descend and pass below the Boeing.

### 3.3 TCAS - Correct Operation (Launceston)

The airspace around Launceston is Class E; aircraft may operate under Visual Flight Rules (VFR). In these circumstances, the basis of collision avoidance between aircraft (even if one aircraft is flying Instrument Flight Rules (IFR) under ATC) is solely by "see and be seen".

On 24 December 2003 a Boeing 737 flying (IFR) was inbound from the north to Launceston on the Flinders Island track. At 29 NM north of Launceston, the crew contacted Air Traffic Control (ATC) and reported that they were on descent to 9,000 ft. The B737 crew was cleared for a visual approach to runway 32 left. ATC also advised that there was traffic operating low level south of the aerodrome but it would not conflict

The co-pilot was the pilot flying and the pilot in command's attention was primarily focused on maintaining a visual watch for traffic. The pilot in command was also monitoring the aircraft's speed in the descent.

As the B737 passed approximately 8,300 ft, the pilot in command noted an aural TCAS TA and then observed a target on the TCAS display indicating that the traffic was at a level 500 ft below the B737, between the 11 and 12 o'clock position. The B737's rate of descent was immediately reduced and 15 seconds later, with the B737 at 14.2 NM north of Launceston, TCAS issued a TCAS RA to climb.

The conflicting traffic was almost on the reciprocal track, approximately 11 NM north of Launceston. The pilot in command of the B737 took over control and established and maintained a climb rate above the minimum rate required by the TCAS RA until clear of conflict. The crew of the B737 advised ATC of the event and ATC advised that there was no known traffic in the area.

The B737 crew did not visually sight the conflicting traffic at any time. However, the B737's cabin crew reported to the pilot in command that passengers saw the conflict aircraft on the left side of the B737.

The pilot in command reported that based on the TCAS display, the aircraft passed slightly to the left, and certainly within both 1 NM from the B737 and 200 ft below. It was subsequently established that the aircraft was a Tobago being operated under VFR at about 7,500 ft. ATC radar coverage was not available at that altitude in the Launceston area.

The Tobago was maintaining around 7,500 ft and with its transponder operating with altitude data enabled. After

establishing the aircraft north of Launceston, the pilot turned the aircraft to intercept the direct track from Launceston to Flinders Island, the reciprocal track to that of the B737.

The pilot of the Tobago was monitoring the Launceston and Melbourne Centre ATC and heard the initial transmission from the crew of the B737 to Launceston ATC. He noted from that transmission that the B737 was inbound to Launceston on the 009 radial of the Launceston VOR and also believed that the B737 had been cleared to track direct to right base runway 32L.

As the pilot of the Tobago was tracking via the 007 VOR radial he considered that there would be sufficient lateral spacing with the B737 on the 009 VOR radial at the point where they were likely to pass each other. He also considered that the lateral distance between them would increase if the 737 was tracking direct to right base rather than tracking inbound on the 009 VOR radial.

The pilot of the Tobago reported that he had selected the aircraft's navigation, strobe and landing lights 'ON'. He subsequently saw the B737 and he believed that it would pass safely to his right. The pilot reported that he flashed the Tobago's landing lights at the 737 several times, but become concerned when the 737 appeared to turn to the right across the nose of the Tobago. The Tobago pilot reported that he observed the B737 climbing above him 'appearing to come from starboard to port'. However, he said that, as the 737 was ascending in front of the Tobago and at his 11 o'clock position, there was no need to consider whether there should be an alteration of course or a decision to descend.

A review of track and heading information from the B737's flight data recorder (FDR) did not reveal any indication of a tracking change.

The Tobago pilot subsequently advised ATSB investigators that he was aware that the appearance of cross-tracking was probably an illusion which resulted from the strong wind.

After the Tobago pilot heard the crew of the 737 report the TCAS RA event to ATC, he advised ATC that his was the aircraft involved and that he had been operating VFR.

The pilot calculated that the aircraft would pass each other at about 15 NM from Launceston, at which point, with 2 degrees between their respective tracks, there would be 0.5 NM lateral spacing between the aircraft with the Tobago passing to the right of the B737. The available evidence suggests that the aircraft passed each other about 12 NM from Launceston which, using the same calculation method, would lead to 0.4 NM lateral spacing between the aircraft. However, these calculations do not take into account navigation aid or tracking tolerances and the actual spacing may have been significantly closer.

### 3.3.1 Observations

The pilot of the Tobago considered separation would be adequate given the 2 degree difference in track from

Launceston. However, this did not make allowance for expected tolerances.

The Tobago was not seen by the crew of the B737 in spite of them maintaining an explicit watch; this illustrates the limitations of "see and be seen".

TCAS observed the Tobago and generated Traffic and Resolution Advisory correctly. The B737 crew followed the Advisory and threat was avoided; a typical TCAS encounter.

## 4 Conclusions

TCAS is installed in some 20,000+ aircraft worldwide and has proven to add a significant reduction in collision risk. Some airlines have a policy of flying in certain airspace only if TCAS is fitted and operating normally. The commercial value of safety is reflected in the reduced insurance premium for TCAS equipped aircraft.

Lessons learnt from TCAS include ...

A major element in the rapid take up and acceptance of TCAS was the ability of TCAS to provide a worthwhile level of protection as soon as it was fitted to an aircraft. Other system designs only provided protection when threat aircraft had been fitted. In today's commercially focused world, a business case which promises benefit at some nebulous time in the future and is dependent on may others playing the game, is unlikely succeed. A system which never transitions into service does not contribute benefit.

Especially for a Safety Critical System, a clear functional Specification and design Principles need to be recorded to ensure that future system modifications and enhancements do not inadvertently detract from the prime function of the safety system – safety.

Existing systems should be reviewed from time to time to assess if new technology or increased user acceptance allow an increased performance to be achieved.

In well engineered systems, human behaviour is likely to be the dominant contributor to system failure. The end users of the system need to thoroughly considered and involved in all system designs. The expected human involvement and performance needs to be explicitly defined and people educated and trained accordingly. HMI, training and human behaviour are a major challenge.

Careful consideration and allowance for cultural and legal factors may be necessary to ensure the maximum benefit of the safety system is realised.

Few systems, when first fielded, are perfect. Monitoring of in-service performance is essential to optimising system performance. Modern recording devices and media make extensive continuous logging cheap and practical. The ability to reproduce and analyse incidents facilitates system improvement and allows authoritative explanation of system behaviour.

## 5 Further Reading

Safer Skies with TCAS – Special Report Office of Technology Assessment Feb 1989  
Congress of the United States; Office of Technology Assessment

Report into TCAS incident and Airmiss between British Airways and Korean Air on 28th June 1999  
Andrew Rose, British Airways

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[www.bfu-web.de](http://www.bfu-web.de)

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John Law  
<http://www.eurocontrol.int/acas/webdocs/Training%20Brochure%20version%202.pdf>

Eurocontrol ACAS II Bulletin 1  
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Eurocontrol ACAS II Bulletin 3  
Eurocontrol ACAS II Bulletin 4  
<http://www.eurocontrol.int/acas/>

AlliedSignal (Honeywell) TCAS wall poster (diagrams).

Honeywell Web Site  
<http://www.honeywelltcas.com/>

ICAO Air Traffic Management (PANS-ATM) - Doc 4444  
[www.icao.int](http://www.icao.int)

ICAO Procedures for Air Navigation Services, Aircraft Operations - Doc 8168  
[www.icao.int](http://www.icao.int)