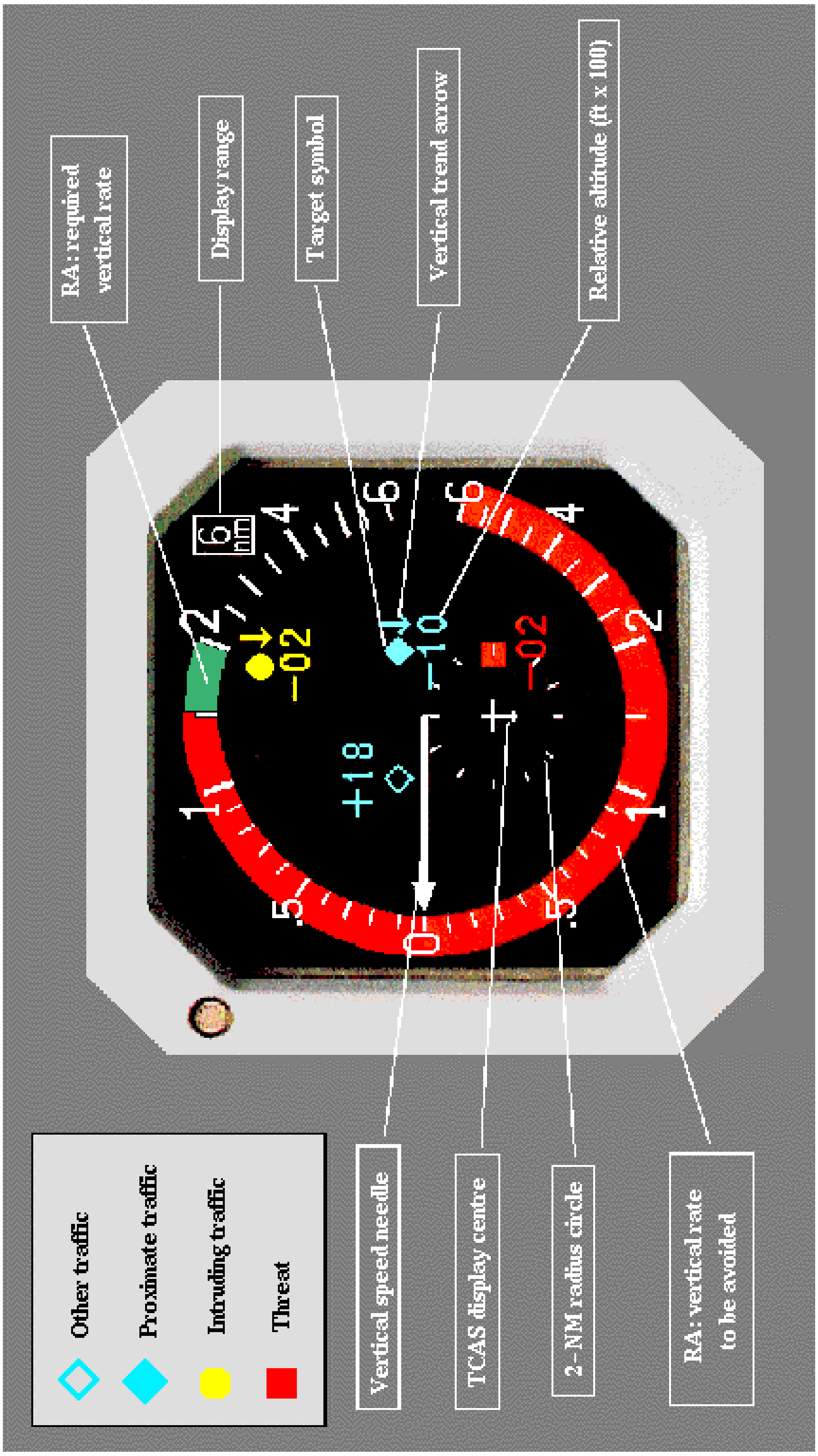
RA: required vertical rate
Display range
Target symbol
Vertical trend arrow
Relative altitude (ft x 100)
Other traffic
Proximate traffic
Intruding traffic
Threat
Vertical speed needle
TCAS display centre
2-NM radius circle
RA: vertical rate to be avoided

ACAS II

NOTE

This document is designed for the training of people involved in the implementation and the use of the Airborne Collision Avoidance System (ACAS). However, it is not, per se, designed for the complete training of controllers or pilots. The principal and essential technical and operational features of ACAS are introduced. For a deeper knowledge, the reader is advised to refer to ICAO and RTCA documentation listed in the bibliography section.

John Law
ACAS Programme Manager

This brochure has been translated and adapted, in the framework of the European Project: ACASA (ACAS Analysis), from a document produced by CENA (Centre d'Etudes de la Navigation Aérienne - France), entitled " Livret d'information ACAS ".

CENA and EUROCONTROL have contributed to the development of this document.

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General introduction

Historical background

Over the years, air traffic has continued to increase. The developments of modern air traffic control systems have made it possible to cope with this increase, whilst maintaining the necessary levels of flight safety. However, the risk of airborne collision remains. That is why, as early as the fifties, the concept and initial development of an airborne collision avoidance system, acting as a last resort, was being considered.

A series of mid air collisions occurred in the United States, initiating the further stages of the system's development.

- In 1956, the collision between two airliners, over the Grand Canyon, spurred both the airlines and the aviation authorities to continue the system development studies.
- In 1978, the collision between a light aircraft and an airliner over San Diego led the FAA (Federal Aviation Administration) to initiate, three years later, the development of **TCAS (Traffic alert and Collision Avoidance System).**
- Finally, in 1986, the collision between a DC-9 and a private aircraft, at Cerritos, required the FAA, based on a Congressional mandate, to issue, in 1989, new aviation legislation, which required some categories of American and foreign aircraft to be equipped with TCAS for flight operations in US airspace.

In parallel to the development of TCAS equipment, ICAO (International Civil Aviation Organisation) has developed, since the beginning of the eighties, standards for **Airborne Collision Avoidance Systems (ACAS)**.

ACAS principles

ACAS is designed to work both autonomously and independently of the aircraft navigation equipment and ground systems used for the provision of air traffic services.

Through antennas, ACAS interrogates the ICAO standard compliant transponders of all aircraft in the vicinity. Based upon the replies received, the system tracks the slant range, altitude (when it is included in the reply message) and bearing of surrounding traffic.

The main feature of ACAS, which was first proposed by Dr John S. Morell in 1955, is that it functions according to time criteria and not distance. From several successive replies, ACAS calculates a time to reach the CPA (Closest Point of Approach) with the intruder, by dividing the range by the closure rate. This time value is the main parameter for issuing alerts and the type of alert depends on its value. If the aircraft transmit their altitude, ACAS also computes the time to reach co-altitude.

ACAS can issue two types of alert:

- Traffic Advisories (TAs), which aim at helping the pilot in the visual search for the intruder aircraft, and by alerting him to be ready for a potential resolution advisory;
- Resolution Advisories (RAs), which are avoidance manoeuvres recommended to the pilot. When the intruder aircraft is also fitted with an ACAS system, both ACAS' co-ordinate their RAs through the Mode S data link, in order to select complementary resolution senses.

ACAS was officially recognised by ICAO on 11 November 1993. Its descriptive definition appears in Annex 2; its use is regulated in PANS-OPS and PANS-RAC. In November 1995, the Standards And Recommended Practices (SARPs) for ACAS II were approved, and they appear in Annex 10.

Types of ACAS

Three types of ACAS exist.

- ACAS I provides TAs (no international implementation is planned at the ICAO level);
- ACAS II provides TAs, and RAs in the vertical plane;
- ACAS III provides TAs, and RAs in both the vertical and horizontal planes.

As far as these equipments are concerned, only TCAS, built by three American manufacturers, complies with ICAO ACAS standards, these being TCAS I for the ACAS I standards and TCAS II for the ACAS II SARPs. No ACAS III equipment currently exists, and none is likely to appear in the near future, because of technical and operational difficulties.

The alerts issued by ACAS II depend on the transponder mode of the intruder:

- there can be no alert if the transponder is inactive, not compliant with ICAO standards;
- TAs if the transponder is active and complies with ICAO standards;
- RAs if the transponder is altitude reporting and complies with ICAO standards.

TCAS II development

TCAS II development, within the framework of the FAA programme, started in 1981. Throughout the eighties, the performance evaluations, carried out by airlines, contributed to the gradual enhancement of the TCAS II equipment, until version 6.0 was reached.

In April 1989, ICAO decided to carry out a worldwide operational evaluation of TCAS II, to determine system performance and to identify any problems. The two main evaluations started, in the United States in June 90, and in Europe in March 91.

The system improvements suggested, as a result of TCAS II evaluations', led to the development and release of Version 6.04a in 1993. The principal aim of this version was the reduction of nuisance alerts, which were occurring at low altitudes and during level-off encounters.

After the implementation of Version 6.04a, further operational evaluations were carried out with the same objective, and proposed performance improvements led to the development of Version 7.0. This was approved in December 1997 and became available at the beginning of 1999. Version 7.0 will further improve TCAS compatibility with the air traffic control system. The most significant enhancements are the introduction of a horizontal miss distance filter and 25-foot vertical tracking, compatibility with RVSM (Reduced Vertical Separation Minima) operations and the reduction of electromagnetic interference.

Towards a world-wide mandatory carriage

The first mandatory carriage of an airborne collision avoidance system, TCAS II, was required for flight in the United States airspace with effect from 30 December 1993. All civil turbine-engined aircraft carrying more than 30 passengers and flying within American airspace must be equipped with TCAS II.

From this date, the number of long range aircraft, fitted with TCAS II and operating in European airspace continued to increase, although the system carriage and operation was not mandatory. However, the continuing studies and evaluations demonstrated the safety benefits of TCAS II and some airlines commenced equipping their fleets.

In 1995, the EUROCONTROL Committee of Management approved an implementation policy and schedule for the mandatory carriage of an ACAS II in Europe. This was then ratified by the European Air Traffic Control Harmonisation and Integration Programme (EATCHIP) Project Board.

The approved policy requires that:

- from 1st January 2000, all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 15,000 kg or a maximum approved passenger seating configuration of more than 30 will be required to be equipped with ACAS II, and
- from 1st January 2005, all civil fixed-wing turbine-engined aircraft having a maximum take-off mass exceeding 5,700 kg, or a maximum approved passenger seating configuration of more that 19 will be required to be equipped with ACAS II.

The mandatory carriage of ACAS II is also being implemented in other States, including Argentina, Australia, Chile, Egypt, India, Japan; etc.

This gradually increasing implementation of the use of ACAS II, arising from the perceived safety benefits of the equipment, and the 1996 mid-air collision in India, between a Saudi Boeing-747 and a Kazakh Illyshin76, initiated the ICAO proposal for world-wide mandatory ACAS II carriage, including cargo aircraft, phased in from 2003 and 2005, and based upon the rules of applicability in the European policy.

In order to guarantee the complete effectiveness of ACAS II, ICAO has mandated the carriage and use of pressure altitude reporting transponders, which are a pre-requisite for the generation of RAs.

After the mid-air collision between a German Air Force Tupolev 154 and a US Air Force C-141 transport aircraft, off Namibia in September 1997, urgent consideration was given to the need to equip military transport aircraft with ACAS II. This is now in hand.

Technical description of TCAS II

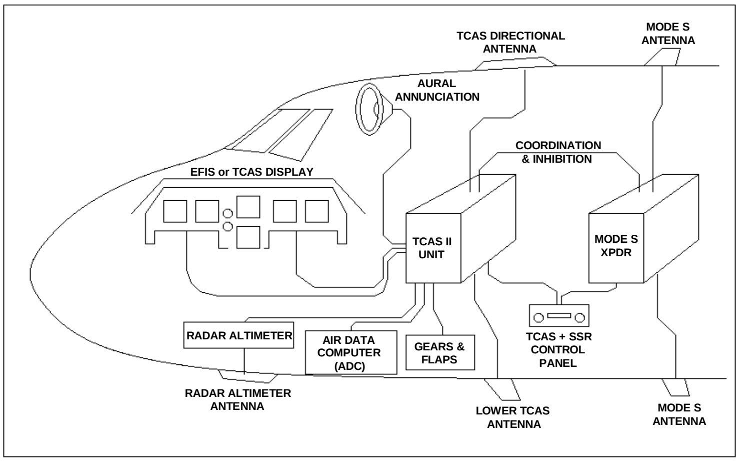


Figure 1: TCAS II block diagram

System components

Figure 1 shows the block diagram of the TCAS II system. A TCAS II is composed of:

a computer unit - which performs airspace surveillance, intruder tracking, threat detection, avoidance manoeuvre determination and the generation of advisories;
a TCAS control panel - incorporated into that of the transponder. It is a 3-position selector:
- " Stand-by ": TCAS is off;
- " TA Only ": only TAs can be issued;
- " Automatic " or " TA/RA ": normal TCAS operation.

two antennas - one fitted to the top of the fuselage and the second to the bottom. The top antenna is directional to enhance intruder surveillance. These antennas are separated from the transponder's antenna. The interrogations are transmitted on 1030 MHz and the replies are received on 1090 MHz, the same frequencies used by SSR (Secondary Surveillance Radar). TCAS operation is linked to the transponder's operation to avoid self-tracking;
a connection with the Mode S transponder - to issue complementary and co-ordinated resolution advisories, when both aircraft are equipped with TCAS;
a connection with the altimeter - to obtain pressure altitude, and/or with the on board Air Data Computer (ADC) if fitted;
a connection with the radar altimeter – on the one hand to inhibit RAs when the aircraft is in close proximity to the ground, and on the other hand to determine whether aircraft tracked by TCAS are on the ground;
loudspeakers - for the aural annunciations;
screens - to display the relevant data.

Additionally some other data, relating to aircraft performance are also taken into account, such as, landing gear and flap status, operational performance ceiling, etc.

However TCAS II **is not connected** to the autopilot, nor the FMS (Flight Management System). TCAS II remains independent and will continue to function in the event of the failure of either of these systems.

Cockpit presentation

The cockpit presentation provides limited information on adjacent traffic, TAs and RAs, and aural annunciations.

The traffic information display system is designed to aid visual acquisition of an intruder. It indicates the relative horizontal and vertical position of other aircraft, in the vicinity, by measuring the replies from their transponders.

1 Traffic display symbology

The own aircraft is shown as an arrowhead or aeroplane-like symbol coloured white or blue.

Targets are displayed by different symbols, according to their ACAS status:

a **hollow blue or white diamond -** for non-intruding traffic;
a **solid amber circle -** for intruders (i.e., which trigger a TA);
a **solid red square -** for threats (i.e., which trigger an RA).

Non-intruding traffic, which are within 6 NM and 1200 ft from own aircraft, are called proximate traffic and are differentiated from other traffic by a **solid white or blue diamond**. In the event of an advisory, this symbol indicates that the aircraft is not the intruder generating the advisory, when the closest traffic may not necessarily be the most threatening.

Each symbol is displayed, on the screen, according to its relative position to own aircraft. The display accuracy depends on the selected scale. When the 10 NM scale is in use the positional accuracy is approximately +/- 1 nautical mile in range and approximately +/- 10 degrees in bearing.

Vertical data is also shown, with the relevant symbol, when the intruder is reporting altitude. The relative altitude is displayed in hundreds of feet, above the symbol if the intruder is above own aircraft and below the symbol in the opposite case. In some aircraft, the flight level of the intruder can be displayed instead of its relative altitude. Additionally an arrow is shown when the target aircraft is climbing or descending at more than 600 fpm.

2 Classical instrumentation

Traffic and advisories are shown on a liquid crystal display, which also includes the Instantaneous Vertical Speed Indicator (IVSI). A 2-NM radius circle is shown by dots or lines around the own aircraft symbol. The display range can vary from 4 to 30 NM ahead of own aircraft.

An RA is shown by the display of a red arc, which indicates the range of vertical speeds, which are to be avoided. A green arc, shown next to the red arc, indicates to the pilot that he should manoeuvre the aircraft to reach the required vertical speed, shown in the green arc, while limiting the altitude deviation.

Note: If there is more than one threat, two red arcs may flank the range of the required vertical speeds.

Figure 2 shows an example of a TCAS display in a classical non 'glass' instrument cockpit.

Figure 3 shows some examples of RAs.

3 EFIS

On Electronic Flight Instrument System (EFIS) cockpit displays TCAS information is shown on the Primary Flight Display (PFD) for RAs and the Navigation Display (ND) for the traffic display.

Two PFD concepts exist:

display on the artificial horizon: a resolution advisory is shown by a red or orange trapezoid area showing the pilot flight attitude values, which are to be avoided. This provides direct guidance on the pitch angle to be achieved by the pilot. This form of display does not include any fly-to green area.

display on the vertical speed indicator: the RA is shown in the same way as in 'classic' cockpits. A red area marks the range of vertical speeds to be avoided, a green area indicates to the pilot the required vertical speed, while limiting the deviation from the ATC cleared flight level.

Figures 4 and 5 show some examples of EFIS instrumentation.

4 Aural annunciations

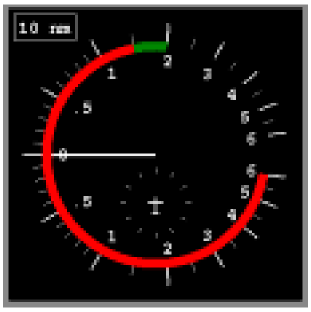
Loud speakers located in the cockpit alert the crew, by means of aural annunciations, of TCAS advisories. The aural messages are detailed in the table below, according to the type of advisory: Traffic Advisory (TA) or Resolution Advisory (RA).

Advisory type	Downward sense	Upward sense
TA	Traffic, traffic	
Initial preventive RA	Monitor vertical speed	Monitor vertical speed
Corrective RA	Descend, descend	Climb, climb
Strengthening RA	Increase descent, increase descent	Increase climb, increase climb
Weakening RA	Adjust vertical speed, adjust	Adjust vertical speed, adjust
Reversing sense RA	Descend, descend NOW	Climb, climb NOW
RA with altitude crossing	Descend, crossing descend, descend, crossing descend	Climb, crossing climb, climb, crossing climb
RA to maintain vertical speed	Maintain vertical speed, maintain	Maintain vertical speed, maintain
RA to maintain vertical speed with altitude crossing	Maintain vertical speed, crossing maintain	Maintain vertical speed, crossing maintain
RA to reduce vertical speed	Adjust vertical speed, adjust	Adjust vertical speed, adjust
RA termination message	Clear of conflict	

Table 1: TCAS II aural annunciations

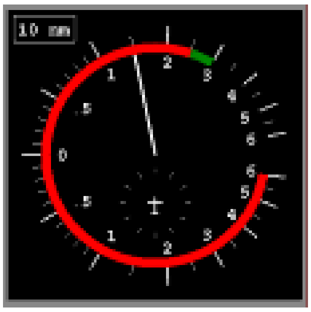
Figure 2: RA on a classical TCAS display

Descend



Climb

Adjust vertical speed
(weakening advisory)



Increase climb
(strengthening advisory)

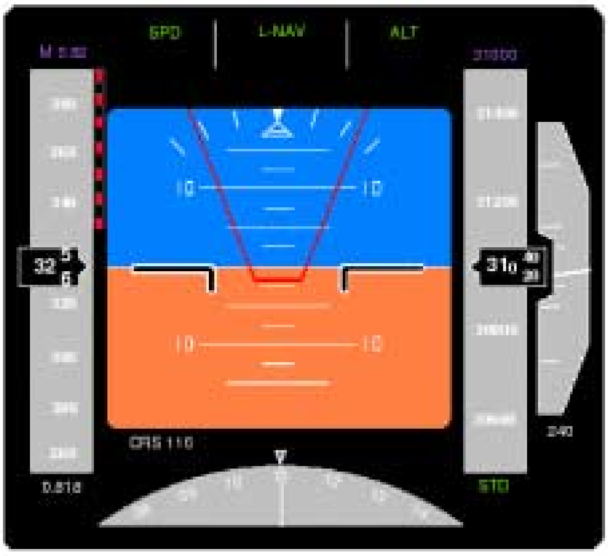
Maintain vertical speed
(maintain climb)

Adjust vertical speed
(reduce rate of descent)

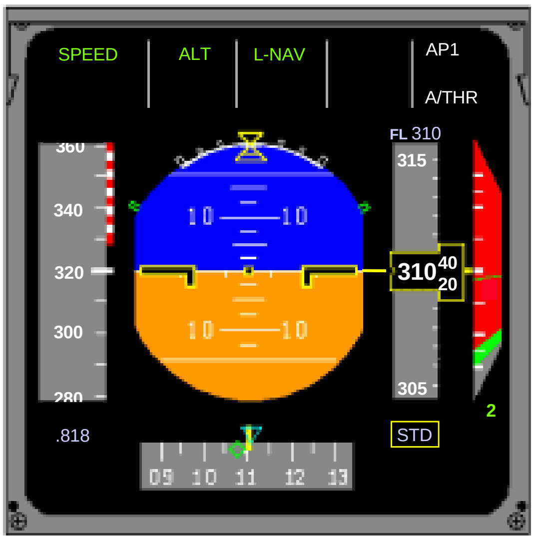
Adjust vertical speed
(multi-threat advisory)

Monitor vertical speed

Figure 3: IVSI showing examples of RAs



RA on the artificial horizon



RA on the Vertical Speed Indicator (VSI)

Figure 4: EFIS - examples of PFD

Figure 5: EFIS - Navigation Display in "ROSE" mode with traffic display

ACAS in the operational environment

The operational evaluation of TCAS II events, carried out in Europe between1991 and 1995, demonstrated the efficiency of TCAS II as an airborne collision avoidance system and identified a certain number of principles for the use of the system. Some of these principles are now included within both European and ICAO regulations, and make the basis for the practical training of pilots and controllers.

Regulations

1 ICAO

Annex 2 shows the official definition of ACAS:

“ **An aircraft system based on secondary surveillance radar transponder signals which operates independently of ground-based equipment to provide advice to the pilot on potential conflicting aircraft that are equipped with SSR transponders. ”**

PANS-RAC - Doc. 4444 defines the conduct and responsibilities of controllers providing a service to ACAS-equipped aircraft:

- the provision of air traffic services (i.e., establishing and maintaining separations and preventing collisions) shall be **identical whether the aircraft is ACAS-equipped or not**. This means that **the controller remains responsible for establishing and maintaining the relevant ATC separation as long as no RA is being followed by the aircrew**.
- when a pilot reports a manoeuvre, due to an RA, the controller shall not attempt to modify the aircraft trajectory, but shall provide relevant traffic information (if possible).

The use of ACAS equipment by aircrew is described in PANS-OPS - Doc. 8168 (Operational use of aircraft):

- **the pilot stays in control of the aircraft operation**: “ nothing [...] shall prevent pilots-in-command from exercising their best judgement and full authority in the choice of the best course of action to resolve a conflict. ”
- the pilot shall use ACAS information in accordance with the following safety considerations:
  - the pilot shall **not manoeuvre on the sole basis of a Traffic Advisory**;
  - during an RA, the pilot shall visually monitor the airspace where the intruder is indicated;
  - **the deviation from the ATC clearance shall be the minimum required**, and the pilot shall, after being advised ‘Clear of Conflict’, promptly return to the current clearance;
  - the pilot shall inform the controller about the RA deviation as soon as possible.

The phraseology, to be used by pilots, is only defined for ACAS II:

- TCAS climb (or descend);
- TCAS climb (or descend), returning to [assigned clearance];
- TCAS climb (or descend) completed, [assigned clearance] resumed;
- unable to comply, TCAS resolution advisory.

There is no specific phraseology for the controller who simply acknowledges.

2 Europe and other States

Some differences exist in the regulations for ACAS, depending upon the ICAO Global Region. These differences are described in detail in the ICAO Doc. 7030 “ Complementary Regional Procedures ”, which includes some additional regulations e.g. mandatory dates, etc.

EUROCONTROL has published a specimen Aeronautical Information Circular (AIC) in January 1996, for publication by the aviation administrations of the ECAC States, the content of which is similar to Doc. 7030.

Operational use

1 Use by pilots

The evaluation of TCAS II performance in Europe and the monitoring of its implementation have demonstrated that this equipment has already improved flight safety. In reportedly dangerous situations TAs have made visual acquisition of intruders possible, in sufficient time to avoid any risk of collision.

However, some problems related to the stress induced, in aircrew, by the RA have been identified.

- An RA sometimes causes pilots to deviate, from their ATC clearance, far more than necessary or required. Deviations greater than 1000 ft have been recorded and the mean deviation is around 650 ft.
- Pilots are often slow to report the initial deviation to the controller and subsequently to return to the given ATC clearance. The official phraseology is sometimes not used and a distracting and disturbing dialogue, about the event, may begin on the frequency. Often the initial RA message from the pilot is not understood by the controller.

Other issues are related to the misuse of data shown on the TCAS display.

- Some pilots request information, or refuse a clearance, based upon aircraft data on the traffic display. This can only be justified if the intruder is not reporting altitude.
- Crews sometimes use the traffic display as a surveillance tool. The information is basic and only shows the approximate relative position of adjacent aircraft, and the risk of misinterpretation is great.
- Aircraft have also been observed turning, on the basis of the data shown on the traffic display, without visual acquisition by the aircrew. Such manoeuvres may cause a significant degradation in the level of flight safety.
- Event reports also indicate that some pilots have not reacted to RAs, when they have traffic information from the controller, but have not visually acquired the intruder. In the case of a justified RA event, they lose precious seconds in initiating the conflict resolution manoeuvre. Additionally, if the intruder is also TCAS-equipped, the RA will be co-ordinated. Not following the advisory immediately degrades flight safety.

2 Interactions with ATC

An RA is generally perceived as disturbing, by the controller, due to the aircraft deviation from the given ATC clearance, the subsequent discussion on the RT frequency and the possibility of an induced conflict with a third aircraft. Although the latter possibility is understandable, the controller must understand that TCAS II is able to simultaneously process several intruders, and provide a relevant RA.

Analysis of the events reported in Europe, show that even if multiple threat encounters exist, the actual possibility of such an event is very low.

The main causes of interaction with the air traffic system are:

- **Aircraft levelling off at 1000 ft above or below conflicting traffic** induce many RAs. The TCAS II system is triggered due to aircraft maintaining high vertical speeds when approaching the cleared flight level.
- **Altitude crossing clearances based upon agreed visual separation**, may also initiate RAs, particularly in the aircraft maintaining its cruising level. The provision of traffic information by the controller, does not permit the pilot to ignore the RA issued by TCAS II. However the traffic information will probably minimise the vertical deviation and consequently, the disturbance caused to the controller.
- Advisories issued against some categories of aircraft: **VFR, fighters in operational manoeuvres, etc**. This problem is related as much to the airspace management, in general, as to the function of TCAS II. However, TCAS II is only really effective if the intruding aircraft reports its altitude, and TCAS II was not designed to take into account the high performance manoeuvres of fighters.

PRACTICAL REMARKS

- When controllers are not aware of an RA, and if they are providing the aircraft with instructions for avoiding action, horizontal instructions are more appropriate as they will not adversely affect any vertical manoeuvres required by TCAS II RAs
- TCAS RAs have a very short duration, generally less than 30 seconds. Controllers may not be able to react within this period of time.
- When the message “ Clear of Conflict ” is issued, to the aircrew, the required ATC separation minima may not exist.
- Due to its limitations, TCAS II is not infallible.
- For these reasons, TCAS II must only be considered as a last resort system.

Training

1 Pilots

The problems encountered by pilots in the use of TCAS II can be grouped into four categories:

- poor knowledge of how the system works
- not using standard phraseology;
- misuse of the TCAS display;
- incorrect reactions to RAs.

A particular effort must be made in crew training. Only the correct use of TCAS II, by pilots, will improve the systems integration into the air traffic control environment and its efficiency in terms of improving flight safety.

This training should include two complementary and indivisible parts:

- **theory**: pilots should have a good knowledge of how TCAS works, including the system limitations;
- **simulator practice**: RAs are stressful and require quick and appropriate reactions from the aircrew involved. Therefore, it is necessary to include RA events in the routine flight simulator training exercises, in order to improve aircrew reaction to RAs in real encounters, and to optimise the operational use of TCAS II.

ICAO has recognised the importance of a suitable training programme for pilots and has distributed the SICASP (SSR Improvement and Collision Avoidance System Panel) document " ACAS - Proposed performance-based training objectives " to States Administrations and international aviation organisations.

2 Controllers

Unlike pilots, controllers do not use TCAS II, but have to take it into account when providing aircraft with the relevant ATC service.

In Europe a comprehensive training course has been implemented for both the initial and the recurrent training of European controllers. The training material includes:

- this booklet;
- video-tapes e.g. "ACAS for Controllers";
- several event analysis reports on TCAS II implementation in Europe;
- an ACAS course on slides.

Additionally, CENA, part of the French DGAC, has developed and produced a TCAS II training tool, named RITA (Replay Interface for TCAS Alerts). This tool provides interactive training support and allows the replay of some previously analysed real TCAS events. RITA presents the pilot's view, the controller's view and the transcript of the Radio-Telephony messages, all on the same screen. As the result of co-operative development by CENA and EUROCONTROL, RITA is now available on CD-ROM for PCs, and training courses are also in place.

The first positive results of TCAS II training have been observed. However, the mandatory carriage of ACAS II in Europe commences on the 1st January 2000, and maintaining, or even strengthening, the training effort for all operational staff is very important.

Examples of conflicts solved by TCAS

The following examples are based upon real TCAS events.

1 Loss of separation due to an altitude bust (IFR-IFR)

A is a TCAS-equipped aircraft, which is cleared to climb to FL280. Another TCAS equipped aircraft, B, is maintaining FL290. Both are following the same route.

When aircraft A reaches FL270, the safety net (Short Term Conflict Alert - STCA) triggers. The controller asks the pilot to confirm his heading and to “ maintain flight level 280 due to traffic ”.

A few seconds later, the pilot of aircraft B reports to the controller that he has a TCAS “ Climb ” RA, because of a traffic indicating 800 ft below, and that he is climbing to FL300.

Aircraft A also gets a “ Descend ” RA, which the pilot complies with. The vertical distance between the two aircraft quickly increases due to the TCAS-TCAS co-ordination and the pilots’ prompt reactions.

The analysis of the event showed that aircraft A overshot its cleared level by 400 ft, because of a mistake when selecting the flight level on the autopilot. The radar data update time, including the altitude information on the radar screen, did not allow the controller to detect the aircraft climbing through the cleared level. Without TCAS, aircraft A would have carried on with its climb.

TCAS prevented a real risk of collision. The aircrew error was not detectable by the controller. Both TCAS co-ordinated the RAs issued to the aircrew and issued complementary RAs.

2 Encounter with an uncontrolled VFR (IFR-VFR)

An IFR TCAS-equipped aircraft was cleared to descend from FL260 to FL080. As the aircraft approaches FL110, the pilot received a “ Climb ” RA and climbed to FL117. The intruder was a VFR aircraft with altitude reporting transponder, flying at FL105, without radio contact, in a class E airspace.

The VFR was neither known to the controller, nor displayed on the radar screen (for operational and practical reasons). As the pilots did not achieve visual acquisition, TCAS II provided last resort collision avoidance.

This incident, which could have become a very high risk of near-mid-air-collision (NMAC) without TCAS II, clearly demonstrates the benefit to aircraft operating VFR of having an active transponder, with the altitude reporting function. If the intruder does not report altitude, TCAS II cannot issue an RA.

This incident clearly shows that the protection provided by TCAS II extends to non TCAS-equipped intruders, with altitude reporting transponders, whether controlled or not.

3 Simultaneous processing of multiple threats

A is a TCAS-equipped aircraft, which is maintaining FL370. Another TCAS-equipped aircraft B is maintaining FL350, cruising in the opposite direction along the same route.

Shortly before passing over aircraft B, aircraft A is overflown by aircraft C, which is descending to FL390. Aircraft A’s TCAS issues a “ Descend ” RA. Analysis of this event showed that this RA was not justified by the geometry of the encounter, and was caused by incorrect altitude reports from aircraft C.

The pilot of aircraft A performs an extended and unnecessary descent manoeuvre and, as a result, comes into conflict with aircraft B.

Aircraft A’s TCAS now issues a **composite RA**, which requires the pilot to limit the vertical speed, for both descent and climb.

This incident demonstrates that TCAS II detected the second intruder and took it into account by issuing a multiple threat RA. However, this kind of situation, an induced conflict with another aircraft, which was not involved in the initial encounter, is very rare.

Target surveillance

This chapter describes Version 7 of TCAS II equipment. This version complies with ACAS II SARPs published by ICAO.

The surveillance function

The surveillance function enables a TCAS-equipped aircraft to interrogate the surrounding Mode S and Mode A/C transponders. The requirement is to determine the relative positions and manoeuvres of the intruder aircraft. TCAS can simultaneously track up to 30 aircraft, in a nominal range of 14 NM for Mode A/C targets and 30 NM for Mode S targets.

1. Intruders fitted with Mode S transponders

TCAS surveillance of Mode S equipped aircraft is based on the selective address feature of the Mode S transponder. TCAS listens for the spontaneous transmissions (squitters) sent once per second by Mode S transponders. The individual address of the sender is contained inside the squitter.

Following receipt of a squitter, TCAS sends a Mode S interrogation to the Mode S address contained in the message. TCAS uses the reply received to determine range, bearing and altitude of the intruder aircraft.

TCAS tracks the changes in range, bearing, and altitude of each Mode S aircraft within cover. This data is provided to the collision avoidance logic to determine the requirement for TAs or RAs.

2. Intruders fitted with Mode A/C transponders

TCAS uses a modified Mode C interrogation to interrogate Mode A/C transponders. This interrogation is known as the ‘Mode C only all-call’. Note: TCAS does not know the Mode A code of the intruder aircraft because it does not interrogate Mode A.

The replies from Mode A/C transponders are tracked in range, bearing and altitude. This data is provided to the collision avoidance logic to determine the requirement for TAs or RAs.

In some cases, the Mode A/C transponders can reply to the ‘Mode C only all-call’, without providing any altitude information. TCAS then uses the synchronisation pulse of the reply to initialise and maintain tracking but provides only the range and the bearing for such aircraft. This data is provided to the collision avoidance logic to determine the requirement for TAs. This data is insufficient for the provision of RAs.

Synchronous and non-synchronous garbling problems, and ground-reflected replies, make it more complicated for TCAS to monitor Mode A/C equipped aircraft than those equipped with Mode S transponders.

2.1 Synchronous garble

When a ‘Mode C only all-call’ interrogation is sent by TCAS, all Mode A/C transponders, which receive it, reply. Due to the duration of the reply, all Mode A/C equipped aircraft, whose difference of distance to the TCAS aircraft is low, can produce replies which overlap at the TCAS level. That is described as ‘synchronous garble’.

Various techniques are employed to reduce this phenomenon.

- Algorithms allow the reliable decryption of up to three overlapping replies.
- The combined use of interrogations of variable power and suppression pulses permit the reduction of the number of transponders replying to an interrogation. This technique, known as ‘whisper-shout’, takes advantage of differences between the receiver sensitivity of transponders and the transponder antenna gains of the intruder aircraft.

Another technique for reducing synchronous garble is the use of directional transmissions, which reduces the number of potential overlapping replies. However, slightly overlapping coverage must be provided to ensure 360 coverage.

2.2 Non-synchronous garble

Non-synchronous garble is caused by the receipt of undesired transponder replies, which follow an interrogation sent by a surveillance radar or another TCAS. These replies, called FRUIT (False Replies from Unsynchronised Interrogator Transmissions) are transitory. They are identified and discarded by reply-to-reply correlation algorithms. The probability that a surveillance track based on FRUIT replies will be started and maintained is extremely low.

2.3 Multi-path effect

Avoiding the initiation of surveillance tracks based on multi-path replies is an aspect of TCAS design. The multi-path effect is caused by the reflection of an interrogation by flat ground, which produces more than one reply, to the interrogation, coming from the same aircraft. The reflected reply is of a lower intensity. To control this effect, the direct-path power level is used; it determines the minimum triggering level of the TCAS receiver. This technique, called DMTL (Dynamic Minimum Triggering Level) discards these delayed and weaker signals.

Interference limiting

The surveillance function contains a mechanism limiting electromagnetic interference in the 1030/1090 MHz band. Each TCAS II unit is designed to limit its own transmissions. TCAS II is able to count the number of TCAS units, within cover, due to the broadcast, every 8 seconds, of a 'TCAS presence' message, which contains the Mode S address of the sender. When the number of TCAS units increases, the number and the power of the interrogations are reduced.

Additionally, in dense traffic areas at altitudes lower than FL180, the rate of interrogation, usually 1 per second, becomes 1 per 5 seconds for intruders considered non-threatening, and at least 3 NM from own aircraft, and which would not trigger an advisory for at least 60 seconds. This mechanism is called “ reduced surveillance ”.

These limitations aim to avoid transponder overload due to high levels of TCAS interrogation and the production of FRUIT affecting ATC surveillance radars. The result, in very high-density airspaces, is that the TCAS surveillance range might be reduced to 5 NM.

The collision avoidance logic

This chapter describes Version 7 of TCAS II equipment. This version complies with ACAS II SARPs published by ICAO.

Principle

The collision avoidance logic, or CAS (Collision Avoidance System) logic, is predictive. It is based on two basic concepts: the sensitivity level and the warning time.

The sensitivity level is a function of the altitude and defines the level of protection. The warning time is mainly based on the time-to-go (and not distance-to-go) to the Closest Point of Approach (CPA). The warning time includes an additional range protection in case of low closure rates.

1. Sensitivity level

A trade-off is needed between the protection that the CAS logic must provide and the unnecessary alarms linked to the predictive nature of the logic. This balance is achieved by controlling the sensitivity level (SL), which adjusts the dimensions of a theoretical " protected volume " around each TCAS-equipped aircraft. The sensitivity level depends on the altitude of own aircraft and varies from 1 to 7. The greater the SL, the more protection is provided.

For the pilot, three modes of operation are available: " STAND-BY ", " TA-ONLY " and " AUTOMATIC ". The logic converts these modes into sensitivity levels:

- when " STAND-BY " mode is selected by the pilot (SL=1), the TCAS equipment does not transmit interrogations. Normally, this mode is used when the aircraft is on the ground or when there is a system malfunction.
- in " TA-ONLY " mode (SL=2), the TCAS equipment performs the surveillance function. However, only TAs are provided. The equipment does not provide any RAs.
- when the pilot selects " AUTOMATIC " mode, TCAS automatically selects the SL based on the current altitude of own aircraft. SL 2 is selected when the TCAS aircraft is between 0 and 1000 feet AGL (Above Ground Level) as indicated by the radar altimeter. This SL corresponds to " TA-ONLY " mode. In SLs 3 through 7, TAs and RAs are provided. To determine the sensitivity level required above 2600 ft AGL, the logic uses the pressure altitude (standard setting 1013.25 hPa) indicated by the barometric altimeter.

2. Warning time

In collision avoidance, time-to-go to the CPA, and not distance-to-go to the CPA, is the most important concept. To exploit this idea, the warning time or tau ( ) concept has been developed. Tau is a threshold, which is compared to the time-to-go to the CPA, computed by dividing the slant range, between aircraft, by the closure rate. TCAS uses the tau concept for most of its alerting functions. The tau values are a function of the SL.

In order to avoid an intruder coming very close in range without triggering a TA or an RA, the protection boundaries derived from the tau principle are modified if the closure rate is very low. This modification, referred to as DMOD (Distance MODification), provides an additional protection when the encounters have very low closure rates. The DMOD values are also a function of the SL.

The tau and DMOD values are shown in Table 2. These values are only valid for the general case. However, the RA-related tau values can be reduced for some geometric configurations (such as 1000-ft level off), so as to reduce the number of unnecessary alerts.

Altitude	SL	TAU values (s)		DMOD values (NM)	
		TA	RA	TA	RA
0 - 1000 ft	2	20	no RA	0.30	no RA
1000 - 2350 ft	3	25	15	0.33	0.20
2350 ft- FL050	4	30	20	0.48	0.35
FL050 - FL100	5	40	25	0.75	0.55
FL100 - FL200	6	45	30	1.00	0.80
> FL200	7	48	35	1.30	1.10

Table 2: Alert thresholds related to altitude

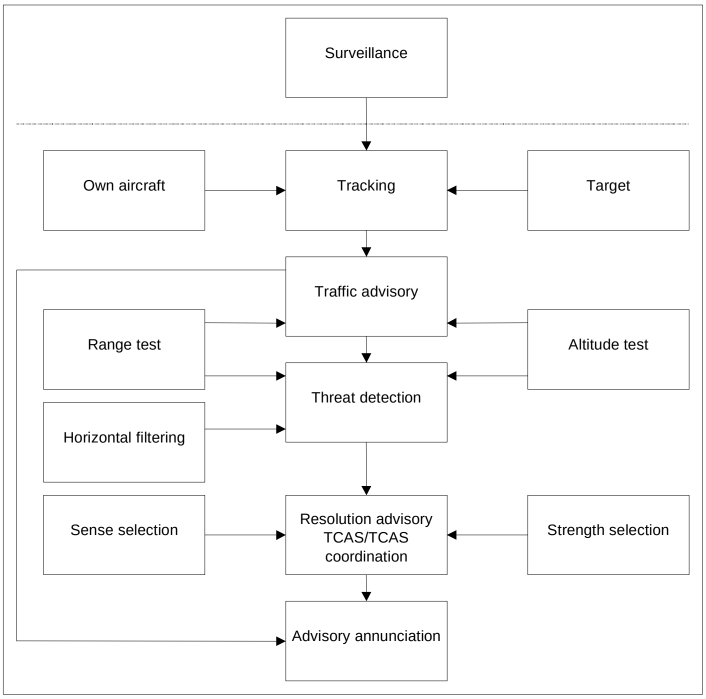


Figure 6: CAS logic functions

CAS functions

TCAS is designed to ensure collision avoidance between any two aircraft, with a closure rate of up to 1200 knots and vertical rates as high as 10,000 fpm.

TCAS significantly improves flight safety. However, it cannot entirely eliminate all risks of collision. Additionally, as in any predictive system, it might itself induce a risk of collision.

In normal operation, the CAS logic works on a 1-second cycle. The CAS logic functions used to perform the collision avoidance task appear in Figure 6. The following description will provide a general understanding of these functions. There are many other parameters, notably those relating to the encounter geometry, that are beyond the scope of this document.

However, a complete description of TCAS II Version 7 logic can be found in the TCAS II MOPS (Minimum Operational Performance Standards) (DO-185A) published by RTCA (Radio Technical Commission for Aeronautics) - USA.

1 Tracking

Using the surveillance reports (slant range, bearing and altitude) provided each second (every five seconds in case of “ reduced surveillance ”), the CAS logic computes the closure rate of each target within surveillance range, in order to determine the time in seconds to CPA, and the horizontal miss distance at CPA. If the target aircraft is equipped with an altitude-coding transponder, the CAS logic calculates the altitude of the target at CPA. The intruder’s vertical speed is obtained by measuring the time it takes to cross successive 100-foot or 25-foot altitude increments, which depends upon the type of altitude coding transponder.

The CAS logic uses the data from own aircraft pressure altimeter, either directly from the altitude encoder or ADC. In this way, it determines own aircraft altitude, vertical rate, and the relative altitude of each target.

The outputs from the tracking algorithm (target range, horizontal miss distance at CPA, closure rate and relative altitude of the target aircraft) are supplied to the traffic advisory and threat detection algorithms.

When below 1,700 ft AGL, the CAS logic estimates the altitude of the intruder above the ground, using own pressure altitude, own radar altimeter and the pressure altitude of the intruder. As noted on Figure 7, if this altitude is less than 380 ft, TCAS considers the target to be on the ground, and so does not generate any TA or RA alarm.

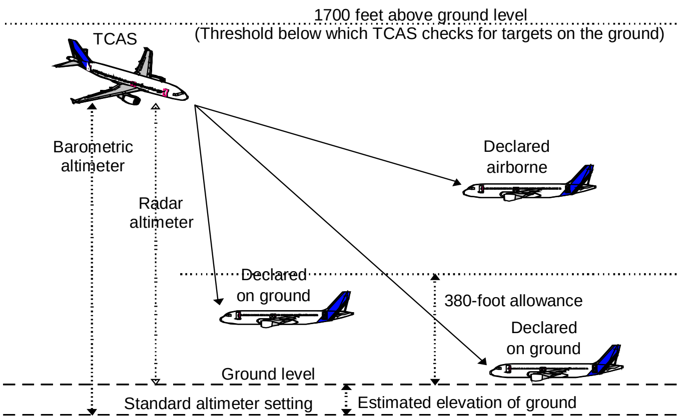


Figure 7: Target on-the-ground determination

2. Traffic advisory

The traffic advisory function uses a simplified algorithm, similar to the RA generation logic but with greater alert thresholds (see Table 2). The vertical triggering thresholds for TAs are 850 ft above and below the TCAS-equipped aircraft below FL420 and 1,200 ft above FL420.

A non-altitude reporting target will trigger the generation of a TA if the range test is satisfied, on the basis of the same tau values associated with the RA.

If an intruder is not the cause of a TA, but is located within 6 NM and 1200 ft of the TCAS-equipped aircraft, it will be displayed as proximate traffic.

3.Threat detection

Range and altitude tests are performed on each altitude-reporting target, every cycle. Both must be satisfied for a target to be declared a threat.

Horizontal alert thresholds are not based on the range at a given time but on the time-to-go to the CPA. This value depends on the speeds and headings of the aircraft involved. For a given intruder, the theoretical " protected volume " around the TCAS-equipped aircraft is generally a truncated sphere of a radius equal to the norm of the relative speed vector multiplied by the time tau. The volume is also laterally truncated by a function of horizontal filtering, or Miss Distance Filtering (MDF). The MDF reduces the number of unnecessary alerts for encounter geometries where the horizontal range, projected at CPA, is sufficient to preclude a collision avoidance manoeuvre. The filter is theoretically effective for values twice those of DMOD.

Generally, for a conflict geometry with a low vertical closure rate, the vertical triggering thresholds for RAs range from 600 to 800 ft, depending on the altitude of own aircraft. For a high vertical closure rate, an RA is triggered as soon as the estimated time to the moment when the intruder and the own aircraft will be at co-altitude is lower than tau values (see Table 2).

Depending on the geometry of the encounter, and the quality of the vertical track data, an RA may be delayed or not selected at all. RAs cannot be generated for non-altitude reporting intruders.

4. Resolution advisory

4.1 Advisory selection

When a threat is declared, TCAS uses a two-step process to select an RA. The first step is to select the sense (upward or downward avoidance) of the RA. Using the results of the vertical and horizontal tracking, the logic models the intruder's path to the CPA. Figure 8 shows the paths that would result if own aircraft climbed or descended at 1500 fpm, taking into account a standard pilot reaction (reaction time of 5 seconds and vertical acceleration of 0.25 g). The CAS logic computes the predicted vertical separation for each of the two cases and selects the sense, which provides the greater vertical distance.

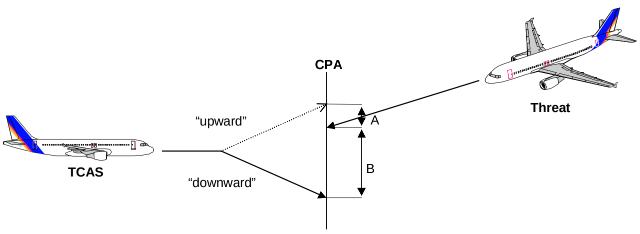


Figure 8: RA sense selection

In the cases where an altitude crossing is projected before the CPA, the CAS logic will pick the sense that avoids crossing, provided that the resulting vertical distance at CPA is sufficient.

Figure 9 illustrates this case. The desired amount of vertical safe distance, referred to as ALIM, varies from 300 ft to 700 ft, depending on own aircraft's altitude regime. If ALIM cannot be achieved, a crossing RA will be issued. However, delaying mechanisms aim at reducing the number of crossings.

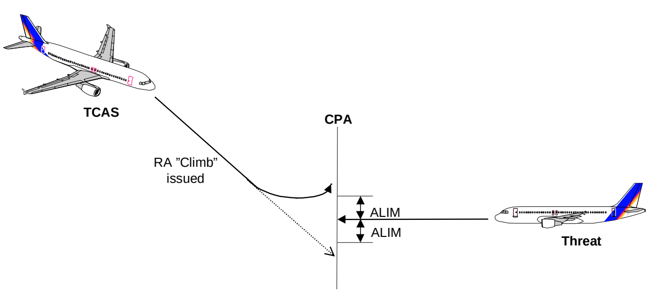


Figure 9: " Non-crossing " RA

Upward sense		Downward sense	
Required rate	**Advisory**	**Advisory**	**Required rate**
+2500 fpm	Increase Climb	Increase Descend	-2500 fpm
+1500 fpm	Climb	Descend	-1500 fpm
+1500 fpm	Reversal Climb	Reversal Descend	-1500 fpm
+1500 fpm	Crossing Climb	Crossing Descend	-1500 fpm
+4400 fpm > V > +1500 fpm	Maintain Climb	Maintain Descend	-4400 fpm < V < -1500 fpm
V > 0 fpm	Don't Descend	Don't Climb	V < 0 fpm
V > -500 fpm	Don't Descend > 500 fpm	Don't Climb > 500 fpm	V < +500 fpm
V > -1000 fpm	Don't Descend > 1000 fpm	Don't Climb > 1000 fpm	V < +1000 fpm
V > -2000 fpm	Don't Descend > 2000 fpm	Don't Climb > 2000 fpm	V < +2000 fpm

Table 3: Resolution advisories

The second step in selecting an RA is to select the strength of the advisory. The least disruptive vertical rate manoeuvre that will still achieve safe vertical distance is selected. Advisories, which do not modify the aircraft vertical rate (preventive advisories), can be generated if the ALIM criterion is already satisfied. Possible advisories and associated climbing/descending rates are listed in Table 3.

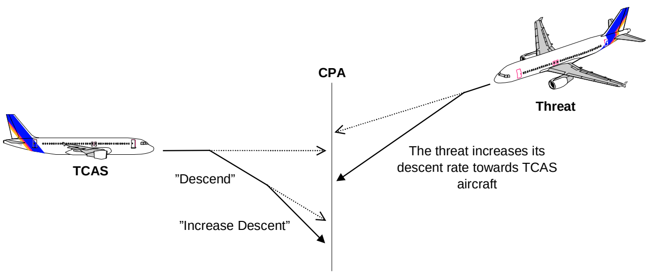


Figure 10: “ Increase-vertical-rate ” RA

4.2 RA's follow-up

During the course of the encounter, advisory strength is continuously evaluated, and can be modified either by increasing it if necessary, or by weakening it if the threat reduces. Weakening the RA should reduce the vertical deviation.

After selecting the RA, occasionally a threat aircraft may manoeuvre vertically in a manner that thwarts the RA. The TCAS-equipped aircraft will then have to: either increase its vertical rate from 1500 to 2500 fpm, or reverse the manoeuvre sense. Only one sense reversal is possible during a single conflict. Examples of such manoeuvres (increased vertical rate and reversed sense) are shown in Figures 10 and 11.

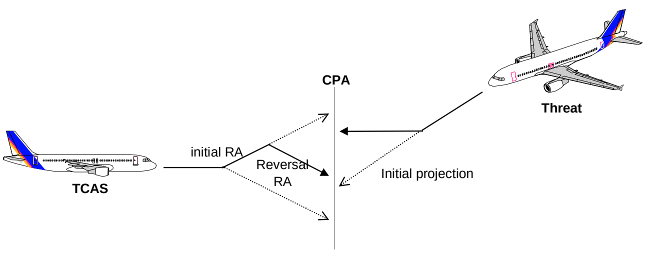


Figure 11: “ Sense-reversal ” RA

The CAS logic may inhibit a “ Climb ” or “ Increase climb ” advisory in some cases due to aircraft climb performance limitations at high altitude, or in the landing configuration. These limitations are known by the logic, which will then choose a viable alternative RA. The limitations are set beforehand by the certification authorities according to the type of aircraft. For all aircraft, “ Increase descent ” advisories are inhibited below 1450 ft AGL. All RAs are inhibited below 1000 ft AGL.

4.3 Multi-threat logic

TCAS is able to handle multi-threat situations either by attempting to resolve the situation with a single RA, which will maintain safe vertical distance from each of the threat aircraft, or by selecting an RA that is a composite of non-contradictory climb and descend restrictions.

4.4 RA termination

As soon as the intruder ceases to be a threat (when the range between the TCAS aircraft and threat aircraft increases or when the logic considers that the horizontal distance at CPA will be sufficient), the resolution advisory is cancelled and a clear-of-conflict annunciation is issued. The pilot must then return to the initial clearance.

4.5 TCAS-TCAS co-ordination

In a TCAS-TCAS encounter, each aircraft transmits interrogations to the other via the Mode S data-link, in order to ensure the selection of complementary resolution advisories. Co-ordination interrogations use the same 1030/1090 MHz channels as surveillance interrogations and are transmitted at least once per second by each aircraft for the duration of the RA. Each aircraft continues to transmit co-ordination interrogation to the other as long as one is considered as a threat.

Co-ordination interrogations contain information about an aircraft’s intended manoeuvre with respect to the threat. This information is expressed in the form of a complement: if one aircraft has selected an “ upward-sense ” advisory, it will transmit a message to the threat, restricting the threat’s solution of RAs to those in the “ downward-sense ”. After co-ordinating, each TCAS unit independently selects the RA’s strength in relation to the conflict geometry.

The basic rule for sense selection in a TCAS-TCAS encounter is that before selecting a sense, each TCAS must check if it has received an intent from the threat. If this is so, TCAS complies with the threat aircraft expectations. If not, TCAS selects the sense, which best fits the encounter geometry.

In the vast majority of cases, the two aircraft see each other as threats at slightly different moments in time. Co-ordination proceeds as follows: the first aircraft selects the RA sense, based on the encounter geometry, and transmits its intent, the second aircraft then selects the opposite sense and confirms its complementary intent.

However, the two aircraft may happen to see each other as a threat simultaneously and, therefore, both select a sense based on the encounter geometry. In this case, there is a probability that both will select the same sense. Should this happen, the aircraft with the higher Mode S address will detect the incompatibility and will reverse its sense before issuing the RA.

5 Advisory annunciation

The CAS logic sets the flags, which control the aural annunciations and the display of information. The logic inhibits the aural annunciations below 400 ft AGL.

Priority, above that for TCAS II TAs or RAs alerts, is given to the aural annunciations linked to stall warnings, GPWS (Ground Proximity Warning System), windshear detection, etc.

6 Air/ground communications

Using the Mode S Data Link, TCAS can downlink RA reports to Mode S ground sites. Also, during an RA, every eight seconds TCAS generates a spontaneous message containing information on the current advisory.

CONCLUSIONS

ACAS is a last resort tool designed to prevent mid-air collisions between aircraft. The technical features of the system provide a significant improvement in flight safety and this has now attained universal recognition in the world of aviation. However, one must be aware that ACAS is not a perfect system. ACAS cannot preclude all collision risks and the system may, marginally, induce an additional risk. Consequently, it is essential that ATC procedures are designed to provide flight safety without any reliance upon the use of ACAS.

On board an aircraft, TAs and RAs generated by TCAS II are not of the same level of urgency as alarms for fire, depressurisation or risk of collision with the ground. However, they are very important contributions to the safety of the flight. TAs and RAs are unplanned events, which call for fast and appropriate reactions from the crew, and therefore require specific training. Nevertheless, even in aircraft with a TCAS II onboard, the crew must continue to maintain a visual lookout to avoid collisions, because some aircraft, either do not transmit their altitude via the transponder and thus can only be the basis for a TA, or are invisible to the TCAS II system because they are not equipped with a transponder.

Controllers, though aware of the improved flight safety, in the airspace, due to the increasing deployment of TCAS, also see some drawbacks. It is therefore essential that controllers have a good knowledge of the system’s characteristics and of the procedures used by aircrew. Controllers are also required to provide the same ATC service, especially with regard to traffic information or the maintenance of the relevant ATC separation, whether the aircraft are fitted with TCAS or not.

Generally speaking, the implementation of TCAS II will bring a whole range of safety-related benefits when the ATC system provides a high quality service and all airborne aircraft report their pressure-altitude via the transponder, and pilots correctly follow the RA issued by the TCAS II system.

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ABBREVIATIONS

ACAS	Airborne Collision Avoidance System
ACASA	ACAS Analysis
ADC	Air Data Computer
AGL	Above Ground Level
AIC	Aeronautical Information Circular
CAS	Collision Avoidance System
CENA	Centre d'Etudes de la Navigation Aérienne
CPA	Closest Point of Approach
DMOD	Distance MODification
DMTL	Dynamic Minimum Triggering Level
EATCHIP	European Air Traffic Control Harmonisation and Integration Programme
EFIS	Electronic Flight Instrument System
EUROCONTROL	European Organisation for the Safety of Air Navigation
FAA	Federal Aviation Administration
FL	Flight Level
FMS	Flight Management System
FRUIT	False Replies from Unsynchronised Interrogator Transmissions
ft	feet
fpm	feet per minute
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IVSI	Instantaneous Vertical Speed Indicator
MDF	Miss Distance Filtering
MHz	Megahertz
MOPS	Minimum Operational Performance Standards
ND	Navigation Display
NM	Nautical Miles
NMAC	Near-Mid-Air-Collision
PFD	Primary Flight Display
RA	Resolution Advisory
RITA	Replay Interface for TCAS Alerts
RTCA	Radio Technical Commission for Aeronautics
RVSM	Reduced Vertical Separation Minima
SARPs	Standards And Recommended Practices
SICASP	SSR Improvement and Collision Avoidance Systems Panel
SL	Sensitivity Level
SSR	Secondary Surveillance Radar
STCA	Short Term Conflict Alert
TA	Traffic Advisory
TCAS	Traffic Alert and Collision Avoidance System
VFR	Visual Flight Rules
VSI	Vertical Speed Indicator
XPDR	Transponder

NOTES

TCAS II does not provide:

- Warning of loss of standard separation
- Prevention of close encounters
- Surveillance supporting lateral manoeuvres

ACAS II

TCAS II is a last-resort safety function to prevent mid-air collision when the primary means of separation has failed