Performance Assessment of Pilot Compliance with Traffic Collision Avoidance System Advisories Using Flight Data Monitoring

Guidance Material – 3rd Edition

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Abbreviations and Acronyms

ACAS	Airborne Collision Avoidance System
ACTF	Accident Classification Task Force
AGL	Above Ground Level
ANSPs	Air Navigation Service Providers
AP	Auto Pilot
ASR	Air Safety Report
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
CFIT	Controlled Flight into Terrain
CPA	Closest Point of Approach
FAA	Federal Aviation Administration
FD	Flight Director
FDA	Flight Data Analysis
FDAP	Flight Data Analysis Program
FDM	Flight Data Monitoring
FDR	Flight Data Recorders
FDX	Flight Data Exchange
FMS	Flight Management Systems
FOQA	Flight Operational Quality Assurance
FSTD	Flight Simulation Training Devices
GPWS	Ground Proximity Warning System

ICAO	International Civil Aviation Organization
IFALPA	International Federation of Air Line Pilots' Association
IFR	Instrument Flight Rule
IVSI	Instantaneous Vertical Speed Indicator
MAC	Mid-air Collison
MTE	Multi-threat encounter
OIPR	Opposite Initial Pilot Response
PF	Pilot Flying
PM	Pilot Monitoring
PTTF	Pilot Training Task Force
RA	Resolution Advisory
RARR	Resolution Advisory Required Rate
SARP	Standards and Recommended Practices
SOP	Standard Operating Procedures
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TAWS	Terrain Avoidance and Warning System
V/S	Vertical Speed
VSI	Vertical Speed Indicator

Objective

Similar to the previous editions of the guidance material, this third edition has been prepared jointly by IATA and EUROCONTROL and is designed to gain further insight on pilots' support compliance with advisories generated by Traffic Alert and Collision Avoidance System (TCAS), as well as TCAS operational mode selection and serviceability. This guidance provides an updated information on technical and operational issues applicable to TCAS Resolution Advisory (RA) in order to facilitate operational monitoring. Surveillance data from core European airspace was analysed by EUROCONTROL, to assess pilot compliance with TCAS RAs.

Introduction

The development and implementation of the TCAS was driven by aviation accidents. TCAS is an airborne system designed to provide collision advice against suitably equipped intruders and to increase awareness of the flight crew of nearby aircraft. Up till this day, TCAS has proven to be very successful at protecting aircraft from mid-air collisions (MAC) and resolving threats.

Currently, TCAS II is the only system that meets the criteria of Airborne Collision Avoidance System (ACAS), which is the International Civil Aviation Organization (ICAO) terminology and is included in the ICAO Standards and Recommended Practices (SARPs).

Note: The acronyms TCAS and ACAS are used interchangeably in the document.

Before we move on in our discussion, it is worth outlining the current status of TCAS System. There are two types of TCAS systems in operational use today, TCAS I and TCAS II, both provide the flight crew with a cockpit display indicating the presence of a transponding 'intruder', but they differ by their alerting capability.

TCAS I system warns of potential conflicts by providing a traffic advisory (TA), which is announced "Traffic, Traffic", but it does not provide any resolution advice. TCAS I system provides TAs to assist the pilot in the visual acquisition of intruder aircraft.

TCAS II equipment provides a second level of alert called a RA. This alert directs the flight crew to make a vertical manoeuvre to avoid the intruding aircraft.

Note: TCAS II does not provide RAs in the lateral direction.

After its introduction in the late 1990s, TCAS II version 7.0 has been the subject of monitoring. A number of issues detected in it led to the development of version 7.1. Version 7.1 incorporated several improvements over version 7.0, one of them was the replacement of the "Adjust vertical speed, adjust" with a new "Level off, level off" RA.

The recently developed **ACAS X system**, expected to become operational in the foreseeable future, is an improved system which development was funded by the United States Federal Aviation Administration (FAA). The ACAS X system is intended to bring enhancements to both surveillance and the advisory logic. (See page Appendix A "Future of Collision Avoidance: ACAS X" – An extract from the EUROCONTROL Operational Safety Study: TCAS RA not Followed).

How does TCAS work

TCAS II works independently of the aircraft navigation, flight management systems (FMS), and Air Traffic Control (ATC) ground systems. While assessing threats, the system does not consider ATC clearance, pilot's intentions nor FMS input. TCAS II is not connected to the autopilot, except the Airbus Autopilot/Flight Director (AP/FD) TCAS capability, which provides automated responses to RAs.

The AP/FD TCAS mode is developed to ensure further safety in traffic avoidance situations by eliminating the need to switch out of one mode and into another during TCAS manoeuvres. This system combines the AP/FD and the TCAS to provide vertical speed guidance based on a TCAS target and best avoidance manoeuvre in case of conflicting air traffic. It also avoids or reduces pilot overreaction, enhances safety, and increases passenger comfort during the manoeuvre.

When there is a risk of collision, TCAS issues two levels of advisory alerts. The first level is the TA and aims to warn pilots of potential conflict and assist them in visual acquisition. The second level is the RA, which recommends a vertical manoeuvre. It directs the pilots to change or limit the vertical rate to avoid a collision, so a prompt and accurate pilot response to all RAs is particularly important.

RAs are rare events, but when they occur, the situation may be critical, thus correct, and immediate flight crew action is required, unless it would jeopardize safety of the aircraft. Any delayed or incorrect flight crew response may negate the effectiveness of the RA, their actions will be the most important single factor affecting the performance of the TCAS system. If the pilots decide not to respond to an RA, they not only negate the safety benefits provided by its own TCAS system, but also jeopardizing safety of all other aircraft involved in the encounter. Operational experience has shown that the correct response by flight crew is dependent on the effectiveness of the initial and recurrent training in TCAS procedures. Training can prepare pilots to successfully fly the rarest and most challenging of RAs.

This 3rd Edition is not, per se, designed for the complete training of pilots or any stakeholders.

In 2020, EUROCONTROL conducted a study analyzing surveillance recording of TCAS RA events for the period of one year over the core European airspace to assess if pilots are responding to TCAS RA as required. The analysis covered 1,176 RAs of over 8 second duration, i.e. a duration long enough to give the pilot a chance to respond. Technically, and in accordance with ICAO provision, a response to an initial RA is expected within 5 seconds.

Moreover, the same data set indicates that a number of aircraft operate daily in core European airspace with TCAS out of service or with TCAS in a TA-only mode. Therefore, in all these cases, this negates the effectiveness of, and the safety benefit provided by the TCAS system.

EUROCONTROL Study

Two separate approaches were taken to assess pilot compliance criteria: "**Method A**", which examines the vertical rates of aircraft after the RA and compares these against the thresholds which are published in the IATA/EUROCONTROL Guidance Material. **"Method A"** follows the IATA/EUROCONTROL Guidance Material strictly. "*Method B*" applies less stringent compliance criteria in case the pilot needs to significantly change vertical rate to comply with RA. In effect **"Method B"**, gives credit to a pilot having to significantly change vertical rate (e.g. from climb to descent) even if the final required vertical rate has not yet been met.

Moreover, in **"Method B"** an additional classification *Weak response* is added for RAs during which the pilot has made an adjustment in vertical speed in the required direction, but insufficient in vertical speed or acceleration to fulfil the RA vertical speed.

Pilot Responsibility

As mentioned in our previous editions, for the current TCAS II system to work as designed and to mitigate a risk of mid-air collision, an immediate and correct flight crew response to TCAS RA is required, unless it would jeopardize the safety of the aircraft. This means that pilots will at times manoeuvre contrary to ATC instructions or disregard ATC instructions. In accordance with the ICAO Airborne Collision Avoidance System (ACAS) manual (ref ICAO Doc. 9863), ACAS anticipates the following response from pilots to RAs:

a) the pilot will respond within 5 seconds to the first RA;
b) the vertical acceleration will be 0.25 g until the required vertical rate is achieved;
c) for subsequent RAs the pilot will respond within 2½ seconds and with 0.25 g except for RA reversals and increase rate RAs; and
d) for RA reversals and increase rate RAs, the pilot will respond with 0.35 g.

Pilots must not manoeuvre contrary to the RA as that could result in a collision with the threat aircraft. However, in case of a TCAS RA manoeuvre contrary to other critical cockpit warnings, pilots should respect those other critical warnings – responses to stall warning, wind shear, and Ground Proximity Warning System / Terrain Avoidance and Warning System (GPWS/TAWS) take precedence over an ACAS RA, particularly when the aircraft is less than 2,500 feet above ground level (AGL).

In brief, the flight crew is expected, in case of an RA event, to act immediately as follows:

- Follow the RA as indicated, unless doing so would jeopardize the safety of the aircraft;
- Do not assume an aircraft, which is in visual contact or depicted on the TCAS display to be the conflicting traffic. It may not be the only aircraft to which the TCAS is responding;
- Disengage the autopilot and follow the RA smoothly and promptly unless your aircraft has an autopilot flight director TCAS guidance mode and is performing the RA manoeuvre correctly by flying the commanded vertical speed (V/S);
- During RA, pilots should closely monitor the correct responses of the autopilot in the automatic TCAS mode (if installed) at all times. The pilot flying (PF) must disengage the autopilot and fly the aircraft manually if the commanded V/S is not maintained by the autopilot/flight director auto TCAS mode;
- Follow the RA even if there is a conflict between the RA and an ATC instruction;
- Immediately notify the appropriate ATC unit of any RA which requires a deviation from the current ATC instruction or clearance;
- Whenever the RA requires a climb while the aircraft is in landing configuration, a go-around should be executed;
- As soon as the Clear of Conflict message is received return to the last assigned flight level or seek alternative ATC instructions;
- Notify ATC when returning to the current clearance;
- Use correct phraseology for the notification of manoeuvres in response to an RA (i.e. [callsign] TCAS RA);
- The PM (Pilot Monitoring) should provide updates on the traffic location and monitor the response to the RA. Proper crew resource management should be applied;
- Report the occurrence in accordance with company safety procedures.

Recurrent training should enhance the understanding of the flight crew on how to respond to RAs, the functionality as well as the limitations of TCAS.

Air Traffic Control Officer (ATCO) Responsibility

Similar to Pilots, Air Traffic Control Officers (ATCO) have a crucial role to play in the avoidance of a potential collision. The general responsibilities of an ATCO during a TCAS RA event are as follows (ref ICAO PANS ATM Doc 4444):

The ATCO

- Should acknowledge notifications made by a pilot that they are responding to a TCAS RA;
- Should not attempt to adjust the flight path of an aircraft responding to an RA event;
- May provide traffic information;
- Should not issue an ATC clearance or instruction to an aircraft involved in an event until the pilot notifies the ATCO that they are resuming the last assigned ATC clearance, or request further instruction;
- Ceases responsibility for providing separation between the aircraft and any other aircraft affected as a direct consequence of the manoeuvre resulting from a TCAS RA;
- Resumes responsibility for providing separation for all affected aircraft, once the pilot informs the ATCO that they are "Clear of the Conflict";
- Should be aware that a pilot may receive excessive responses to a TCAS RA that can be disruptive to ATC and result in additional RAs.

Performance Monitoring

In the event an RA occurs, the flight crew shall be expected to report the circumstances of the occurrence in accordance with the operator safety occurrence reporting procedure. The reporting of the RA by the flight crew is expected to open the safety investigation process.

A procedure should be in place for ATC to secure surveillance data recordings for all reported TCAS events. ATC surveillance data, if available, will contribute to the assessment of the performance of TCAS and in assessing the impact an RA may have on ATC operations. The results can be used to enhance TCAS performance and safety. An example of the EUROCONTROL assessment of pilot compliance with TCAS RA using ATC surveillance data is found in Appendix B.

In addition to the pilot and controllers reports, a complimentary approach to the safety report is the Flight Data Monitoring (FDM) system, also known as Flight Data Analysis Program / Flight Operational Quality Assurance (FDAP/FOQA) programs, which measures and monitors how the aircraft is being flown, through the analysis of data downloaded from an aircraft's on-board flight data recorders at the end of every flight. Events like TCAS RAs are captured by such programs and because of their small number, all RAs must be assessed to identify the root causes, contributing factors and the problematic areas, such as approaches to closely spaced parallel runways, and mitigation actions formulated.

Note: Pilots and flight crew are used interchangeably in the document.

Monitoring Operational Safety Issues (TCAS RA Event)

The structure of the organization has to be taken into account when setting up safety monitoring arrangements. This document suggests the use of FOQA/FDM for the monitoring and follow up of TCAS RA events. The FOQA/FDM program detects a TCAS RA in the flight data. This data is used to analyse RAs associated with close encounters and problematic areas such as approaches to closely-spaced parallel runways as well as flight crew compliance to RAs. The data can also detect whether the flight crew is responding to RAs, delaying response, or responding in the wrong direction. Once the assessment is made, identification and development of mitigation measures will be put in place.

The following questions will help in assessing, controlling or eliminating such events:

Was an Air Safety Report (ASR) filed by the flight crew?

The analyst should check if a safety report was filed. If it is the case, typically this allows the flight crew to be approached and if necessary debriefed. If it is not the case, typically the pilots can only be approached by the FOQA/FDM gatekeeper (depending on airline policies and procedures). On first contact, the flight crew must be asked to file an ASR and it is expected that the pilots will do so.

Was the response to the TCAS RA within time and performance parameters set by the company?

The analyst reviews the flight data to determine whether the response to the TCAS RA was within the required time limit, and if the required vertical rate was followed. This analysis will be attached to the ASR in the company SMS database, allowing the safety officer/manager to determine if the event can be closed or requires follow up with the pilots. In the latter case, an effective method of debriefing is for the safety manager to review the flight data animation with both pilots and, if possible, with a training captain from the fleet. The debriefing should be conducted in a positive spirit as a learning opportunity. Where necessary, the debriefing can be complemented by a training session (that can include flight simulation training devices (FSTD) training) to develop pilots' competencies. In the case where the pilot has not filed a report and his/her identity remains protected a debriefing will be conducted by the FOQA/FDM gatekeeper.

Was the Flight Data Reviewed?

Flight data monitoring can be a powerful tool for an aircraft operator to improve and monitor its operational safety. The aim of FDM is to improve safety through an analysis of information downloaded from an aircraft's on-board recorder. This information can be used by the operator to identify and discover underlying issues that have the potential to negatively affect safety and to allow operators to take appropriate action and modify pilot training. FDM programs are used for detecting exceedances, such as non-compliance to standard operating procedures (SOPs), monitor TCAS RA compliance, or good judgement and flying skills.

Regulations and Operational Guidance

Significant reductions in the occurrences of many of the operational issues such as the number of nuisance advisories and others have resulted from the following improved elements: TCAS logic, training guidance for pilots and controllers, procedures for responding to an RA, operating practices, forms for providing reports on the performance of TCAS, and suggested phraseology to be used for advising the controller of the manoeuvre in response of an RA event.

Key Performance Indicators

In order to allow, if needed, the comparison of TCAS performance and pilot compliance it is recommended that aircraft operators collect, if feasible, the following data (derived from their FDM systems):

- Number of RAs by type (as defined in Tables 1 and 2)
- Number of RAs by type (as defined in Tables 1 and 2) and altitude[1]
- Number of RAs by type (as defined in Tables 1 and 2) and aircraft type
- Number of RAs by type (as defined in Tables 1 and 2) and their duration

The assessment of pilot compliance (Followed – Not Followed – Opposite – Excessive) should be made using the criteria as described in the Compliance assessment methods section below. The assessment of the pilot's compliance evaluation should be made on regular basis to determine if there are any training or safety issues.

Furthermore, a key indicator of the number of RAs per flight hour and per leg should be calculated and its evolution observed as well, as the increase in certain types of RAs (e.g. Level Off RAs) may be an indicator of underlying operational problems (approaching the cleared level with too high a vertical rate).

Conclusion

An operator must establish procedures on how their flight crew should operate aircraft TCAS systems and respond to respective alerts, both TAs and RAs. Broadly speaking, operator procedures should cover topics addressed in this document, as well as related ICAO provisions. These include, but are not limited to:

- Pilot responses to RAs;
- Pilot compliance with RAs;
- Aircraft operations including the use of automation during an RA;
- Phraseology used in response of RA manoeuvre;;
- TCAS training;
- RA reporting;
- Use of FOQA/FDM for monitoring and follow up of TCAS RA events

The risk of a mid-air collision is always present. In addition to the recommendations listed in this document, initial/recurrent and simulator training is crucial not only to ensure that pilots correctly interpret and react to TCAS RAs but also to enhance flight crew understanding of how the TCAS system works, as well as the limitations of TCAS. The pilot's response is a key component of the TCAS system. The consequences of a delayed response, or not reacting to an TA/RA, and responses that are too weak or too aggressive can have a negative impact on the effectiveness of the TCAS system.

In case of a TCAS RA event, the pilot shall report the circumstances by means of ASR. This data, together with the operational data downloaded from an aircraft's on-board computer at the end of every flight (FDM), can be collected, analysed and used by the operator, to identify and discover underlying issues that have the potential to negatively affect safety, and to enable operators to implement appropriate mitigation measures.

[1] The following altitude bands should be used: 1000 – 2350 ft AGL; 2350 ft AGL – FL50; FL50 – FL100; FL100 – FL200; FL200 – FL290; FL290 – FL410 and FL410 and above.

Recommendations

TCAS has been deployed to act as a safety net last resort to mitigate the risk of mid-air collisions by providing flight crew with collision avoidance advice.

In order for TCAS to deliver its safety objective, it is recommended that operators ensure that:

- Their aircraft are equipped with TCAS as mandated and the equipment is maintained as required;
- Dispatch of the aircraft with inoperative TCAS equipment or functions is performed only in accordance with MEL applicable provisions, including the operational (O) and maintenance (M) procedures specified by the MEL;
- Pilots who operate TCAS-equipped aircraft have received the relevant training;
- Approved pilot training programs are implemented for initial and recurrent training;
- If possible, TCAS training manoeuvres should be introduced as a surprise to provide a startle effect;
- Procedures are in place for pilots to report a TCAS event and/or problems with TCAS performance;
- Procedures are in place to use correct phraseology for the notification of the manoeuvre in response to an RA. These procedures are contained in the ICAO PANS-ATM (Doc 4444);
- Procedures are in place to analyse any reported event and problem, and to provide feedback;
- Pilots should use correct phraseology as documented in their SOPs to report RAs and their manoeuvres in response to an RA to ATC;
- Pilots should understand the potential risks of an improper response to an RA;
- Unless otherwise instructed by ATC, when safe, practical, and in accordance with an operator's approved operating procedures, pilots limit vertical rates to 1500 fpm or less when within 1000 ft of assigned altitudes, this will reduce the frequency of unnecessary RAs;
- Foster coordination and collaboration among industry, regulatory authorities, and others to maintain awareness of TCAS monitoring, TCAS training, procedures for responding to TCAS RA;
- Following an RA, or any other significant TCAS event, the pilot and the controller should file an ASR;
- The use of FDM program in the monitoring of TCAS RA compliance and the provision of feedback to training organisations and flight crew involved;
- A systematic review of the TCAS policies and procedures is continuously required. Operators should establish standard operating procedures (SOPs) and standardized training on pilot response to TCAS RAs, including following the RA promptly and accurately even in the presence of contravening ATC instructions;
- Encourage commitment from senior management to creating a working environment and employ procedures that optimizes human/pilot performance in the automated environment; and encourage all stakeholders to actively engage and contribute to safety information sharing groups.

Supporting information

Future of Collision Avoidance

The new approach of ACAS Xa takes advantage of recent advances in 'dynamic programming' and other computer science techniques (which were not available when TCAS II was first developed) to generate alerts using an off-line optimization of resolution advisories.

ACAS Xa

ACAS Xa is a new collision avoidance system, foreseeing a "drop-in replacement" of TCAS II. Instead of using a set of hard-coded rules, ACAS Xa alerting logic is based upon a numeric lookup table optimized with respect to a probabilistic model of the airspace and a set of safety and operational considerations. The system uses the same hardware (antennas and displays) as the current TCAS II system and the same range of RAs – as in TCAS II version 7.1 – is used. There are no changes in the way RAs are displayed and announced to the pilot, with the exception of Maintain Vertical Speed and Crossing Maintain Vertical Speed RAs, which in the ACAS Xa installation is announced using the same aural as for Descend or Climb RAs or Reversal Descent or Reversal Climb RAs (if the Maintain Vertical Speed RA is a reversal RA). Consequently, pilots and controllers would perceive no change in the transition to the new system, which is fully compatible with the current TCAS II system (versions 6.04a, 7.0 and 7.1). The intention is for ACAS Xa to eventually replace TCAS II. However, there is a significant difference between TCAS II and ACAS Xa in the decision as to whether or not to issue an RA; therefore, the timing and types of alerts may vary from what a pilot would expect.

ACAS Xa standards (RTCA DO-385 and EUROCAE ED-256) were finalized in September 2018. Also, the ICAO Document 9863 Airborne Collision Avoidance System (ACAS) Manual – Third edition was published in 2021 includes ACAS Xa provisions. Any guidance regarding the TCAS performance assessment provided in this document is equally applicable to the ACAS Xa system. ACAS Xa RA shall be assessed in the same way as TCAS II version 7.1 RAs.

TCAS Advisories Classification

TCAS provides mid-air collision avoidance by detecting and tracking aircraft proximate to own aircraft.

TCAS II can issue two types of alerts which are announced orally and displayed on the relevant cockpit instruments:

- **Traffic Advisories (TAs)**, which aim to help the pilots in the visual acquisition of the intruder aircraft, and to alert them to be ready for a potential resolution advisory.
- **Resolution Advisories (RAs)**, which are avoidance manoeuvres recommended to the pilot. An RA will tell the pilot the range of vertical rates within which the aircraft should be flown to avoid the threat aircraft. An RA can be generated against all aircraft equipped with an altitude reporting transponder (Mode S or Mode A/C); the intruder does not need to be fitted with TCAS II. When the intruder aircraft is also fitted with a TCAS II system, both systems coordinate their RAs through the Mode S data link, in order to select complementary resolution senses. TCAS II does not detect non-transponder equipped aircraft or aircraft with a non-operational transponder. A TCAS II RA takes precedence over any ATC instructions or clearances.

During the encounter, the RA strength is evaluated every second. Occasionally, the threat aircraft manoeuvres vertically in a manner that thwarts the effectiveness of the issued RA. In these cases, the initial RA is modified to either increase the strength or reverse the sense of the initial RA (when the initially issued RA is no longer predicted to provide sufficient vertical spacing).

If the TCAS logic determines that the response to an RA has provided the sufficient vertical distance prior to the closest point of approach (CPA) (i.e. the aircraft have become safely separated in altitude while not yet safely separated in range), the initial RA will be weakened. This is done to minimize unnecessary deviations from the original altitude.

Collision avoidance logic sets the minimum time limits on RA duration as follows:

- Minimum RA duration (initial RA to Clear of Conflict) – 5 seconds;
- Minimum time before a reversal RA can be issued – 5 seconds;
- Minimum time before weakening RA can be issued – 10 seconds.

When the intruder ceases to be a threat (i.e. when the range between the TCAS II 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 flight crew should then return the aircraft to the last ATC assigned level.

TCAS Operational Assessment

TCAS II is estimated to reduce the risk of mid-air collision by a factor of about 5. The most important single factor affecting the performance of TCAS II is the response of pilots to RAs. At any time, regardless of the level of equipage by other aircraft, the risk of mid-air collision for a specific aircraft can be reduced by a factor greater than three by fitting TCAS II.

The operational evaluation of TCAS II performance using monitoring data has been demonstrated to be an effective means for operators to improve overall flight safety. In many cases, RAs have prevented near mid-air collisions and mid-air collisions from taking place. However, it must be stressed that TCAS II cannot resolve every near mid-air collision and may induce a near mid-air collision if certain combinations of events occur.

Although TCAS II significantly improves flight safety, it cannot entirely eliminate all risks of mid-air collision.

Expected TCAS RA Response

RAs are usually triggered between 15 to 35 seconds from the CPA. The time scales are shorter at lower altitudes. Unexpected or sudden aircraft manoeuvres may cause an RA to be generated with much less lead time.

In the event of an RA, pilots shall respond immediately as indicated using prompt, smooth control inputs unless doing so would jeopardize safety of the aircraft. If the pilot delays the response or decides not to respond to an RA, the flight crew not only negates the safety benefits provided by its own TCAS system, but also decreases the safety benefits to all other aircraft involved in the encounter.

Furthermore, pilots must not decide to manoeuvre contrary to the RA as that could result in a collision with the threat aircraft. However, in case a TCAS RA manoeuvre is contrary to other critical cockpit warnings, pilots should respect those other critical warnings.

For corrective RAs (i.e. RA that instruct the pilot to deviate from current vertical rate) the response should be initiated in the proper direction within 5 seconds of the RA being issued. The change in vertical rate should be accomplished with an acceleration of 0.25g.

For increase and reversal RAs, the vertical rate change should be started within 2½ seconds of the RA being issued. The change in vertical rate should be accomplished with an acceleration of 0.35g.

Pilots should avoid excessive response to RAs. The "Excessive" events generate a risk of followed up conflicts (with a third-party aircraft) when the vertical deviation gets too large or may generate a risk of a Controlled Flight into Terrain (CFIT) accident if an excessive reaction to a downward sense RA occurs close to the ground. Moreover, the "Excessive" reactions create a potential for higher g-forces and potential injury to the aircraft occupants.

In accordance with Chapter 5 of the ICAO Doc 9863 Airborne Collision Avoidance System (ACAS) Manual, a response to RAs should be done by disconnecting the autopilot and by using prompt, smooth control inputs; manoeuvre in the direction and with the vertical rate ACAS required.

To achieve the required vertical rate (normally 1500 ft per minute) on aircraft where the RA is displayed on a vertical speed indicator (VSI), it is recommended that the aircraft's pitch be changed using the guidelines shown in the table below. Referring to the VSI or vertical speed (V/S) tape, the pilot must make further pitch adjustments necessary to place the V/S in the green area or outlined pitch guidance area:

Speed	Pitch Adjustment
.80 MACH	2 degrees
250 KIAS below 10,000 ft	4 degrees
Approach below 200 KIAS	5 to 7 degrees

On aircraft with pitch guidance for ACAS RA displays, RAs shall be responded to by following pitch commands.

Prompt and correct reaction to the weakened RA is important as it will minimize altitude deviations and disruptions to ATC. This will also reduce the possibility of a follow up conflict.

ICAO Annex 6 recommends that the vertical rate should be reduced to 1500 ft/min. or less throughout the last 1000 feet of climb or descent to the assigned altitude when the pilot is made aware of another aircraft or approaching an adjacent altitude or standard flight level, unless otherwise instructed by ATC.

Compliance assessment methods

Two separate approaches are proposed to assess pilot compliance:

- **"Method A"** examines the vertical rates of aircraft after the RA and compares these against the predefined thresholds (see Tables 1 and 2), as originally published in the 1st and 2nd editions of this Guidance Material.
- **"Method B"** is also using the RA target vertical rates specified in Tables1 and 2, with tolerance of ±300ft/min. It also takes a reaction time of 5 seconds by the pilot into account, as well as a ¼g expected limit on acceleration. In effect "Method B", gives credit to a pilot having to significantly change vertical rate (e.g. from climb to descent) even if the final required vertical rate has not yet been met. Figure 1 illustrates a comparison between "Method A" and "Method B".

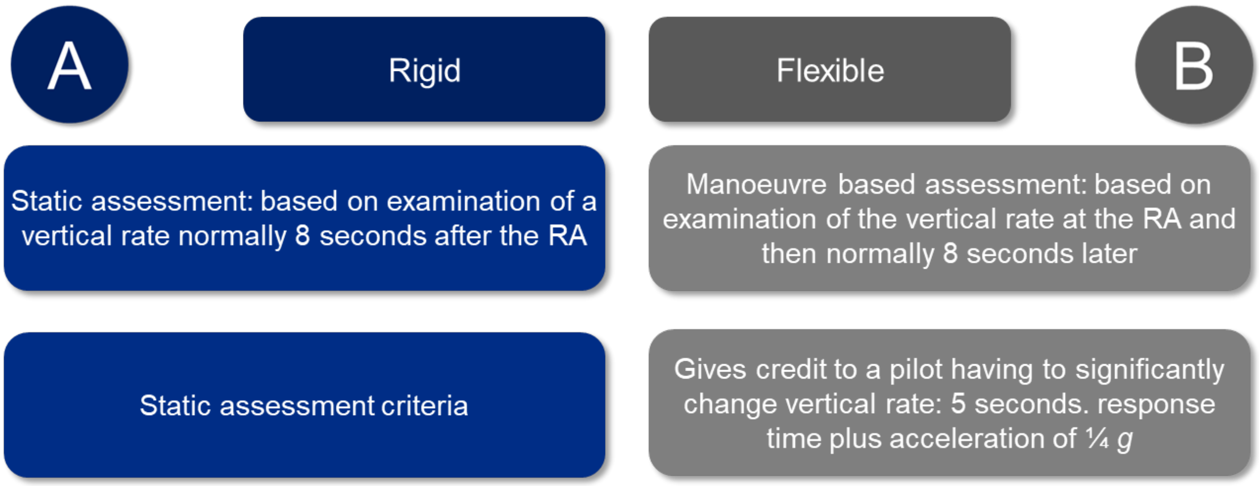


Figure 1: Comparison between Methods A and B

Moreover, each Method comes with some advantages and disadvantages as shown in figure 2 below, so the Users may decide which Method is more suitable for them.

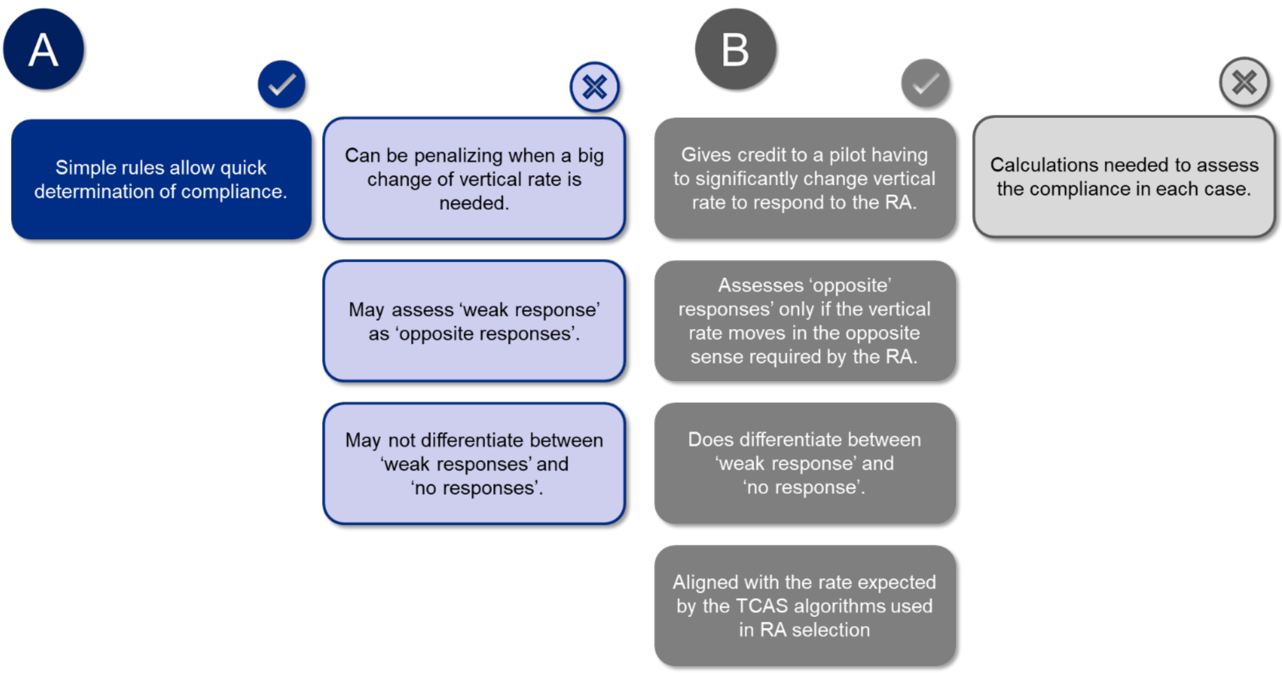


Figure 2: "Method A" and "Method B" Advantages and Disadvantages

For **"Method A",** RA responses are classified as follows:

- **Followed:** when the required vertical rate was achieved (within a margin of 300 ft/min. less than the green arc and 200 ft/min. greater than the green arc.)
- **Not Followed (no response):** when there was no change to aircraft's vertical rate after the RA or the change was not sufficient to meet the vertical rate required by the RA, i.e. the vertical rate remained below 300 ft/min. less than the green arc but more than the opposite sense (expected for the RAs when a change in vertical rate is not required);
- **Opposite:** when the achieved vertical rate was in the opposite vertical sense to the required rate;

- **Excessive:** when the achieved vertical rate exceeded the required rate RA by 200 ft/min. (except for the RAs when the change in vertical rate is not required).

For **“Method B”** , the following pilot response categories have been defined:

- **Followed:** the pilot’s reaction is consistent with a manoeuvre towards the required vertical rate, with the anticipated acceleration and reaction time (including the required vertical rate being achieved);
- **Weak Response:** the pilot has made an adjustment in vertical speed in the required direction, but insufficient in vertical speed or acceleration to fulfil the requirement;
- **Not Followed (no response):** any change in the vertical speed is within the measurement noise (±300 ft/min.) and therefore no response is registered;
- **Opposite:** the change in vertical speed performed by the pilot is in the opposite vertical sense compared to the instruction generated by TCAS;
- **Excessive:** the response exceeds the required vertical rate.

In **“Method B”,** a “*weak response*” classification has been added to accommodate cases when the pilot is responding in the right vertical sense but has not reached the required vertical rate. Otherwise, the response classifications follow broadly the same philosophy.

Figure 3 depicts the response classifications for both *Methods.*

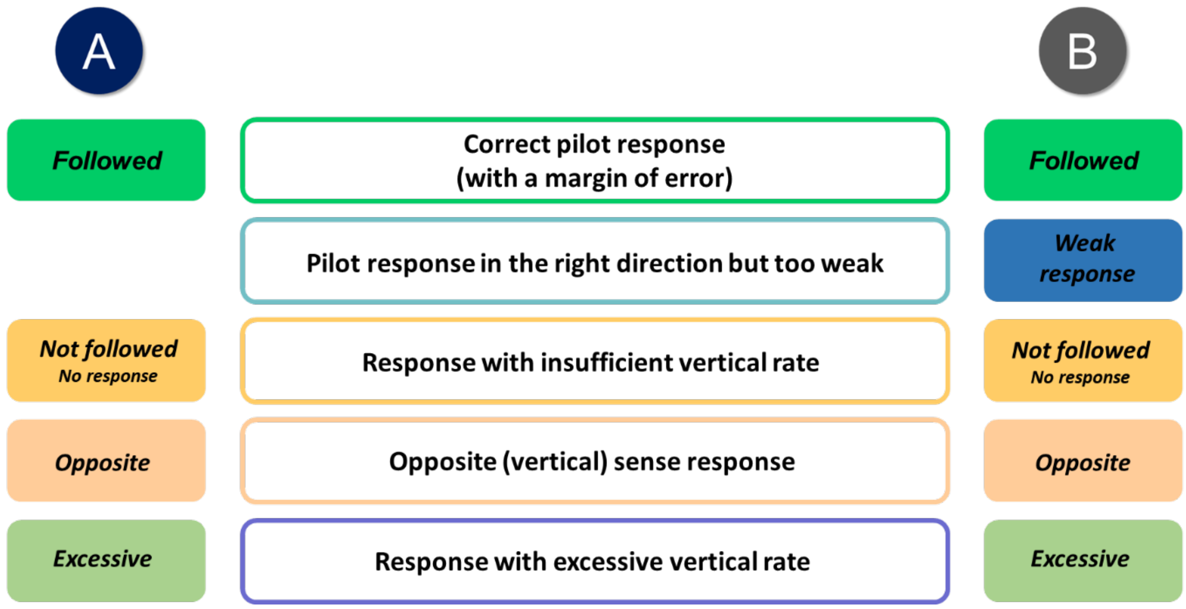


Figure 3: Response classification for “Method A” and “Method B”

Since **“Method B”** requires computations to assess the compliance, an Excel tool is available from IATA and EUROCONTROL for convenience of FDM analysists to grade the compliance. The User guide together with the algorithm used in the Excel tool is available in the Appendix D to this Guidance Material.

Vertical Rates

Table 1 and Table 2 below provide a list of all TCAS II (versions 7.0 and 7.1) and ACAS Xa RAs, associated aural annunciation, Instantaneous Vertical Speed Indicator (IVSI) examples (to show the green/red arc ranges) and vertical rates that are required and prohibited for each of these RAs. These tables list the vertical rates that nominally should be achieved while responding to the corresponding RA. In reality, these rates can rarely be precisely or promptly achieved (e.g. a change from a descent to climb without excessive g-forces will take more time than a change from a level flight to climb). Also, recorders sometimes show imprecision and fluctuations of vertical rates between updates. Therefore, while assessing pilot compliance, a margin needs to be applied to rates listed below.

The vertical rate response ranges (Followed – Not followed – Opposite – Excessive) to allow the assessment using **“Method A”** are also provided in the Tables. To determine the compliance using **“Method B”,** calculations are needed. These can be conducted using the Excel tool mentioned in the previous section.

Given that the green arc is not displayed for preventive RAs (i.e. Monitor Vertical Speed RAs), the rules above cannot be applied to them. The evaluation of these RAs can only be done in the Followed and Opposite categories, as indicated by the red and black arcs.

From a safety point of view the “Not Followed” and “Opposite” events are the most critical and call for particular attention and investigation.

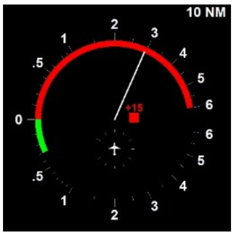
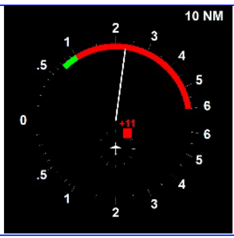
Table 1 below presents the assessment criteria, associated aural annunciation and IVSI examples for initial RAs for TCAS II versions 7.0 and 7.1 as well as ACAS Xa.

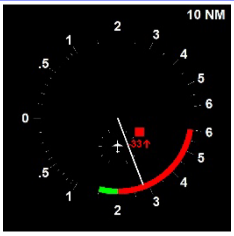
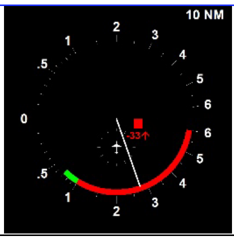
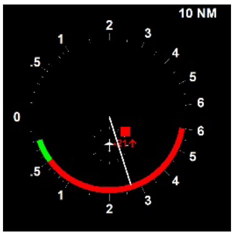
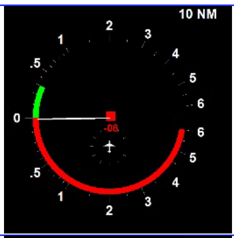
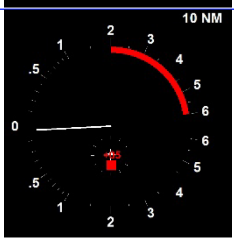
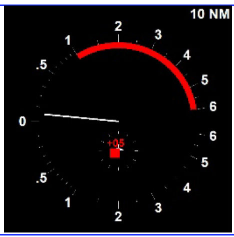
Note: The vertical rate values in the Table below are always express as an integer. Any non-integer values should be round up or down, always away from zero.

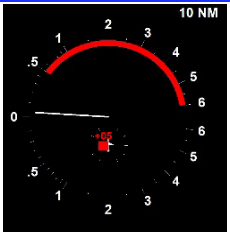
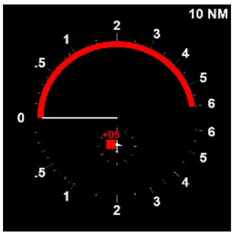
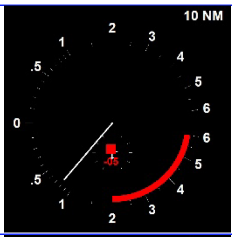
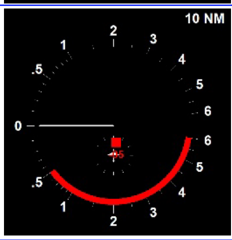
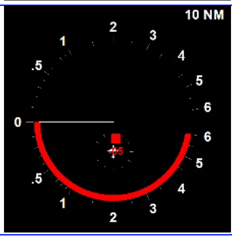
Table 1: Assessment criteria of pilot responses to initial RAs

Resolution Advisory *Aural annunciation*	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	***Method A* Pilot compliance assessment**			
				Followed		**Opposite**	**Excessive**
Climb **Climb, climb**		-6000 – 1500	1500 – 2000	1201 – 2200	0 – 1200	< 0	> 2200
Crossing Climb **Climb, crossing climb; climb, crossing climb**		-6000 – 1500	1500 – 2000	1201 – 2200	0 – 1200	< 0	> 2200
Descend **Descend, descend**		-1500 – 6000	-2000 – -1500	-2200 – -1201	-1200 – 0	> 0	< -2200

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	*Method A* Pilot compliance assessment			
				Followed	Not followed	Opposite	Excessive
Crossing Descend **Descend, crossing descend; descend, crossing descend**		-1500 – 6000	-2000 – -1500	-2200 – -1201	-1200 – 0	> 0	< -2200
Upwards Maintain Vertical Speed **Maintain vertical speed, maintain** a) b) **Climb, climb** c)	Dependent on the encounter and current vertical rate	Vertical rates less than RARR	Vertical rates greater than RARR	RARR – 20% ≤ V ≤ RARR + 40%	0 ≤ V < RARR – 20%	< 0	> RARR + 40%
Upwards Crossing Maintain Vertical Speed **Maintain vertical speed, crossing maintain** a) b) **Climb, crossing climb; climb, crossing climb** c)	Dependent on the encounter and current vertical rate	Vertical rates less than RARR	Vertical rates greater than RARR	RARR – 20% ≤ V ≤ RARR + 40%	0 ≤ V < RARR – 20%	< 0	> RARR + 40%
Downwards Maintain Vertical Speed **Maintain vertical speed, maintain** a) b) **Descend, descend** c)	Dependent on the encounter and current vertical rate	Vertical rates greater than RARR	Vertical rates less than RARR	RARR + 40% ≤ V ≤ RARR – 20%	RARR – 20% < V ≤ 0	> 0	< RARR + 40%

Resolution Advisory *Aural annunciation*	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	***Method A* Pilot compliance assessment**			
				Followed	**Not followed**	**Opposite**	**Excessive**
Downwards Crossing Maintain Vertical Speed **Maintain vertical speed, crossing maintain** a) b) **Descend, crossing descend; descend, crossing descend c)**	Dependent on the encounter and current vertical rate	Vertical rates greater than RARR	Vertical rates less than RARR	RARR + 40% ≤ V ≤ RARR – 20%	RARR – 20% < V ≤ 0	> 0	< RARR + 40%
Downwards Level Off b) c) **Level off, level off**		0 – 6000	-300 – 0	-500 – 300	301 – 500	> 500	< -500
Upwards Level Off b) c) **Level off, level off**		-6000 – 0	0 – 300	-300 – 500	-500 – -301	< -500	> 500
Reduce Climb 2000 ft/min. a) **Adjust vertical speed, adjust**		2000 – 6000	1500 – 2000	1300 – 2300	2301 – 2500	> 2500	< 1300
Reduce Climb 1000 ft/min. a) **Adjust vertical speed, adjust**		1000 – 6000	700 – 1000	500 – 1300	1301 – 1500	> 1500	< 500
Reduce Climb 500 ft/min. a) **Adjust vertical speed, adjust**		500 – 6000	200 – 500	0 – 800	801 – 1000	> 1000	< 0

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	*Method A* Pilot compliance assessment Followed	Not followed	Opposite	Excessive
Reduce Climb 0 ft/min. a) **Adjust vertical speed, adjust**		0 – 6000	-300 – 0	-500 – 300	301 – 500	> 500	< -500
Reduce Descent 2000 ft/min. a) **Adjust vertical speed, adjust**		-6000 – -2000	-2000 – -1500	-2300 – -1300	-2500 – -2301	< -2500	> -1300
Reduce Descent 1000 ft/min. a) **Adjust vertical speed, adjust**		-6000 – -1000	-1000 – -700	-1300 – -500	-1500 – -1301	< -1500	> -500
Reduce Descent 500 ft/min. a) **Adjust vertical speed, adjust**		-6000 – -500	-500 – -200	-800 – 0	-1000 – -801	< -1000	> 0
Reduce Descent 0 ft/min. a) **Adjust vertical speed, adjust**		-6000 – 0	0 – -300	-300 – 500	-500 – -301	< -500	> 500
Preventive Limit Climb 2000 ft/min. a), b) **Monitor vertical speed**		2000 – 6000	n/a	<= 2300	n/a	> 2300	n/a
Preventive Limit Climb 1000 ft/min. a), b) **Monitor vertical speed**		1000 – 6000	n/a	<= 1300	n/a	> 1300	n/a

Resolution Advisory ***Aural annunciation***	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	***Method A*** **Pilot compliance assessment**			
				Followed	**Not followed**	**Opposite**	**Excessive**
Preventive Limit Climb 500 ft/min. [a), b)] **Monitor vertical speed**		500 – 6000	n/a	<= 800	n/a	> 800	n/a
Preventive Limit Climb 0 ft/min. [a), b)] **Monitor vertical speed**		0 – 6000	n/a	<= 300	n/a	> 300	n/a
Preventive Limit Descent - 2000 ft/min. [a), b)] **Monitor vertical speed**		-6000 – -2000	n/a	>= -2300	n/a	< -2300	n/a
Preventive Limit Descent -1000 ft/min. [a), b)] **Monitor vertical speed**		-6000 – -1000	n/a	>= -1300	n/a	< -1300	n/a
Preventive Limit Descent -500 ft/min. [a), b)] **Monitor vertical speed**		-6000 – -500	n/a	>= -800	n/a	< -800	n/a
Preventive Limit Descent 0 ft/min. [a), b)] **Monitor vertical speed**		-6000 – 0	n/a	>= -300	n/a	< -300	n/a

Notes:

- *a) TCAS II version 7.0*
- *b) TCAS II version 7.1*
- *c) ACAS X*

V – AC current vertical rate

RARR – RA required rate (a signed quantity, positive when a climb is required and negative when a descent is required).

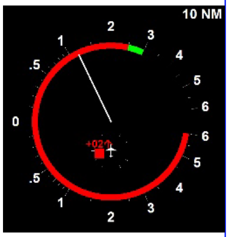
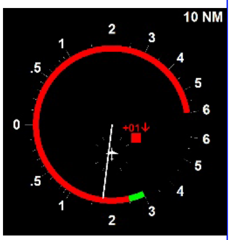
For Maintain Vertical Rate RAs, the Resolution Advisory Required Rate (RARR) value is used. As for these RAs, the required vertical rate RA will vary, depending on the aircraft's vertical rate at the time when the RA was issued. Therefore, the compliance can only be assessed if the required rate has been recorded.

During an encounter, the RA may change. Table 2 below presents the assessment criteria, associated aural annunciation, IVSI examples for subsequent RAs for TCAS II versions 7.0 and 7.1 as well ACAS Xa.

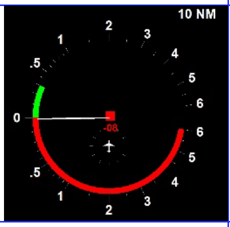
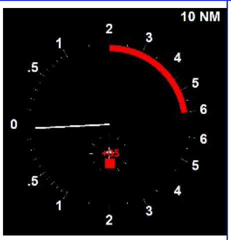
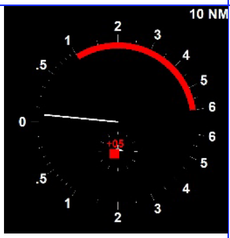
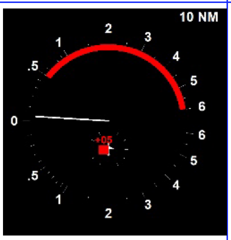
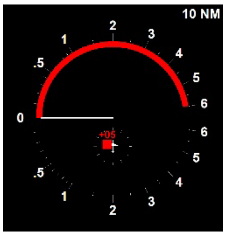
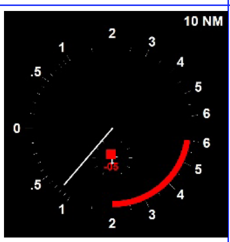
Note: The vertical rate values in the Table below are always express as an integer. Any non-integer values should be round up or down, always away from zero.

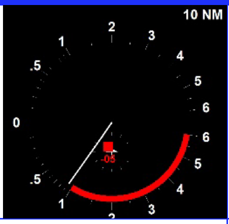
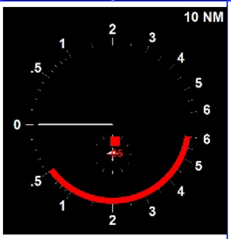
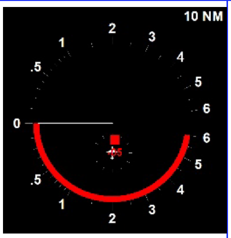
Table 2: Assessment criteria of pilot responses to subsequent RAs

Resolution Advisory ***Aural annunciation***	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	***Method A*** **Pilot compliance assessment** **Followed**		**Opposite**	**Excessive**
Climb **Climb, climb**		-6000 – 1500	1500 – 2000	1201 – 2200	0 – 1200	< 0	> 2200
Crossing Climb **Climb, crossing climb; climb, crossing climb**		-6000 – 1500	1500 – 2000	1201 – 2200	0 – 1200	< 0	> 2200
Reversal Climb **Climb, climb NOW; climb, climb NOW**		-6000 – 1500	1500 – 2000	1201 – 2200	0 – 1200	< 0	> 2200

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	*Method A* Pilot compliance assessment			
				Followed	Not followed	Opposite	Excessive
Increase Climb **Increase climb, increase climb**		-6000 – 2500	2500 – 3000	2201 – 3200	1000 – 2200	< 1000	> 3200
Descend **Descend, descend**		-1500 – 6000	-2000 – -1500	-2200 – -1201	-1200 – 0	> 0	< -2200
Crossing Descend **Descend, crossing descend; descend, crossing descend**		-1500 – 6000	-2000 – -1500	-2200 – -1201	-1200 – 0	> 0	< -2200
Reversal Descent **Descend, descend NOW; descend, descend NOW**		-1500 – 6000	-2000 – -1500	-2200 – -1201	-1200 – 0	> 0	< -2200
Increase Descent **Increase descent, increase descent**		-2500 – 6000	-3000 – -2500	-3200 – -2201	-2200 – -1000	> -1000	< -3200
Upwards Maintain Vertical Speed **Maintain vertical speed, maintain** a) b) **Climb, climb** c)	Dependent on the encounter and current vertical rate	Vertical rates less than RARR	Vertical rates greater than RARR	RARR – 20% ≤ V ≤ RARR + 40%	0 ≤ V < RARR – 20%	< 0	> RARR + 40%

Resolution Advisory *Aural annunciation*	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	***Method A*** **Pilot compliance assessment**			
				Followed	**Not followed**	**Opposite**	**Excessive**
Upwards Crossing Maintain Vertical Speed **Maintain vertical speed, crossing maintain** [a) b)] **Climb, crossing climb; climb, crossing climb** [c)]	Dependent on the encounter and current vertical rate	Vertical rates less than RARR	Vertical rates greater than RARR	RARR – 20% ≤ V ≤ RARR + 40%	0 ≤ V < RARR – 20%	< 0	> RARR + 40%
Downwards Maintain Vertical Speed **Maintain vertical speed, maintain** [a) b)] **Descend, descend** [c)]	Dependent on the encounter and current vertical rate	Vertical rates greater than RARR	Vertical rates less than RARR	RARR + 40% ≤ V ≤ RARR – 20%	RARR – 20% < V ≤ 0	> 0	< RARR + 40%
Downwards Crossing Maintain Vertical Speed **Maintain vertical speed, crossing maintain** [a) b)] **Descend, crossing descend; descend, crossing descend** [c)]	Dependent on the encounter and current vertical rate	Vertical rates greater than RARR	Vertical rates less than RARR	RARR + 40% ≤ V ≤ RARR – 20%	RARR – 20% < V ≤ 0	> 0	< RARR + 40%
Downwards Level Off (weakening) [b) c)] **Level off, level off**		0 – 6000	-300 – 0	-500 – 300	301 – 500	> 500	< -500
Upwards Level Off (weakening) [b) c)] **Level off, level off**		-6000 – 0	0 – 300	-300 – 500	-500 – -301	< -500	> 500

Resolution Advisory	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	*Method A* Pilot compliance assessment			
Aural annunciation				Followed	Not followed	Opposite	Excessive
Reduce Climb 0 ft/min. [a)] Adjust vertical speed, adjust		0 – 6000	-300 – 0	-500 – 300	301 – 500	> 500	< -500
Reduce Descent 0 ft/min. [a)] Adjust vertical speed, adjust		-6000 – 0	0 - 300	-300 – 500	-500 – -301	< -500	> 500
Preventive Limit Climb 2000 ft/min. [a), b)] Monitor vertical speed		2000 – 6000	n/a	<= 2300	n/a	> 2300	n/a
Preventive Limit Climb 1000 ft/min. [a), b)] Monitor vertical speed		1000 – 6000	n/a	<= 1300	n/a	> 1300	n/a
Preventive Limit Climb 500 ft/min. [a), b)] Monitor vertical speed		500 – 6000	n/a	<= 800	n/a	> 800	n/a
Preventive Limit Climb 0 ft/min. [a), b)] Monitor vertical speed		0 – 6000	n/a	<= 300	n/a	> 300	n/a
Preventive Limit Descent -2000 ft/min. [a), b)] Monitor vertical speed		-6000 – -2000	n/a	>= -2300	n/a	< -2300	n/a

Resolution Advisory	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	*Method A* Pilot compliance assessment			
Aural annunciation				Followed	Not followed	Opposite	Excessive
Preventive Limit Descent -1000 ft/min. a), b) **Monitor vertical speed**		-6000 – -1000	n/a	>= -1300	n/a	< -1300	n/a
Preventive Limit Descent -500 ft/min. a), b) **Monitor vertical speed**		-6000 – -500	n/a	>= -800	n/a	< -800	n/a
Preventive Limit Descent 0 ft/min. a), b) **Monitor vertical speed**		-6000 – 0	n/a	>= -300	n/a	< -300	n/a

Notes:

- *a) TCAS II version 7.0*
- *b) TCAS II version 7.1*
- *c) ACAS X*

V – AC current vertical rate

RARR – RA required rate (a signed quantity, positive when a climb is required and negative when a descent is required).

Note: in table 1 and 2 above, for preventative RAs no values are specified for Not Followed and Excessive responses as these RAs do not require a positive response (change in the vertical rate).

No separate guidance is provided for Multi-threat RAs (MTE), i.e. RAs when an own aircraft is simultaneously experiencing two threats. For MTE RAs, the assessment principles listed above should be applied.

Following the compliance assessment, the operator should review the event and debrief the flight crew, using, when applicable, effective visualization software, including instrument panel graphics, displays of relevant aircraft systems, and graphical depiction of the aircraft and location, and gather their feedback on the situation.

Furthermore, a review of operational risks where pilots manoeuvre was too weak, excessive or opposite to the issued RA should also be analysed to understand the underlying causes. The opposite reaction to TCAS RA (e.g. Climb instead of Descend) is of particular concern as it thwarts the effectiveness of TCAS. However, evaluating the magnitude of the reaction is slightly more complicated as every operator and every fleet has different sets of FDM events thresholds. To support the operators with the compliance assessment, the range of vertical rates for each RA are provided in Tables 1 and 2. In order to assess the risk of the event, the airline should cooperate with the Air Navigation Service Provider (ANSP) in whose airspace the event occurred, as the ANSP will have the full picture of the event (ATC actions, other aircraft manoeuvres, etc.)

An effective FDM tool should be able to provide trend analysis on TCAS RA, including flight phases and geographical location.

It should be noted that several aircraft are equipped with the TCAS AP/FD (Auto Pilot / Flight Director) capability. It is a guidance mode which allows the aircraft to automatically fly the RA if the auto pilot is engaged, or the pilot to hand fly the RA by following the flight director commands. While conducting the compliance assessment, it should be determined whether the capability was engaged during the event and, if it was disconnected, the FDAP team should seek to establish why the crew did not use the AP/FD capability.

Furthermore, FDAP teams should review the encounter focusing on the response or lack of response to the TCAS RA, as well as SOP compliance (i.e. disconnecting the AP and FD).

Challenges Associated with Pilot Responses

In some cases, pilots ignore RAs or they respond in the opposite sense. The main reasons given for the noncompliance are proximity to the ground, presumed TCAS II malfunction, misinterpretation of RA alert, giving priority to ATC instruction or performing own avoidance manoeuvre (based on visual acquisition or own judgement). Inappropriate pilot responses severely impair TCAS's performance and increase the risk of a mid-air collision. It is therefore recommended that operators ensure that their pilots receive, in addition to initial and recurrent classroom training, simulator training covering all the RAs and that their instructors select various RA scenarios on their simulators at any time during a simulator session.

A TCAS RA takes priority over an ATC instruction and visual acquisition of traffic as it cannot be guaranteed that the aircraft acquired visually is the same as the intruder detected by the TCAS system, or it may not be the only aircraft to which ACAS is responding.

Note: Stall warning, wind shear and Ground Proximity Warning System / Terrain Avoidance and Warning System (GPWS/TAWS) alerts take precedence over ACAS RAs. Wind shear and GPWS/TAWS warnings will inhibit RAs (TCAS will automatically be placed into TA-only mode).

It is to be noted that any RA that appears to be generated in the absence of a credible threat or not in compliance with the TCAS Standards should be carefully examined and investigated. If needed, these cases should be reported to the manufacturers and/or regulators, as any false RA may be an indication of a problem that needs to be addressed by them. Resolving such issues will generate greater confidence in the TCAS system and encourage flight crews to comply with TCAS RAs.

The interaction between TCAS and transponders is critical. Therefore, any TCAS monitoring program should include provisions for monitoring the performance of transponders; as well as ensuring that periodic testing and installation of transponders, and appropriate calibration, are conducted. The data should then be processed to look for any exceedance and deviations from the flight manual limits and Standard Operating Procedures (SOPs). Additionally, in an event of system malfunction, it is recommended that this event be immediately reported, by means of ASR and maintenance log.

Interaction between Pilots and ATC

Pilots are required to comply with all RAs, even if the RAs are contrary to ATC clearances or instructions, unless doing so would endanger the aircraft. Responding to RAs will, in many cases, cause an aircraft to deviate from its ATC clearance. In such cases, the controller is no longer responsible for separation of the aircraft involved in the RA.

On the other hand, ATC can potentially interfere with the pilot's response to RAs. If a conflicting ATC instruction coincides with an RA, the pilot might assume that ATC is fully aware of the situation and is providing a better resolution – but in reality, ATC cannot be assumed to be aware of the RA until the RA is reported by the pilot.

As soon as possible, as permitted by flight crew workload, pilots must notify the appropriate ATC unit of any RA that requires a deviation from the current ATC instruction or clearance, using suggested phraseology. Procedures in regard to ACAS-equipped aircraft and the phraseology to be used for the notification of manoeuvres in response to a RA are contained in the PANS-ATM (Doc 4444), Chapters 15 and 12 respectively.

Once the RA is reported, ATC is required not to attempt to modify the flight path of the aircraft involved in the encounter.

Cooperating with ATC Authorities (Air Navigation Service Providers - ANSPs)

TCAS RA encounters are typically investigated by Air Navigation Service Provider (ANSPs) and serious cases by State investigation bodies. In these cases, the airline may gain access to surveillance data and other ATC information which would allow making a broader assessment of the event or provide additional information (e.g. in case of incomplete airborne data).

Typically, ANSPs have at their disposal surveillance data and Mode S downlink messages. Surveillance data will allow simulating (recreating) RAs (using specialized software tools); however, this technique may not always be accurate (due to inaccuracy of surveillance data, infrequent updates and data distortion by surveillance tracker). Moreover, some ANSPs use Mode S RA downlink messages. Using the Mode S data link, TCAS II can downlink RA Reports to Mode S ground sensors. This information is provided in the Mode S transponder's 1090 MHz response to an interrogation from a Mode S ground sensor requesting information. RA downlink message will provide information about some but not all details of the issued RA (e.g. the vertical rate limits issued in Adjust Vertical Speed RAs are not part of the downlinked messages). In addition, the Mode S downlink is subject to latency due to the rotating surveillance radar antenna and the exact time of the RA may not be known as the messages are not time stamped.

Some ANSPs also intercept RA broadcast and RA coordination messages for monitoring and investigation purposes. Cooperation with ATC authorities for investigation of critical RA events is necessary and highly recommended.

Pilot training

Many of the operational issues identified can be referred to misunderstandings regarding the operation of TCAS, its capabilities, its benefits, and its limitations. For these reasons, it is essential that pilots and controllers be trained on TCAS operations. Pilots must be trained on how to use the system and to respond to RA in a manner compatible with the system design.

ICAO has recognized the importance of a suitable training program for pilots and controllers. The guidelines for training are contained in the ICAO ACAS Manual (Doc. 9863) and ICAO PANS-OPS VOL III (Doc. 8168).

Amongst other topics, the following should be covered in the pilot training:

- Comply with RAs as indicated on the flight deck instruments;
- Do not manoeuvre in a direction opposite to that indicated by the RA because this may result in a collision;
- Inform the controller of the RA as soon as permitted by flight crew workload after responding to the RA. There is no requirement to make this notification prior to initiating the RA response;

- Be alert for the removal of RAs or the weakening of RAs so that deviations from a cleared altitude are minimized;
- If possible, comply with the controller's clearance, e.g. turn to intercept an airway or localizer, at the same time as responding to an RA; and
- When the RA event is completed, promptly return to the previous ATC clearance or instruction or comply with a revised ATC clearance or instruction.

For Air Traffic Controllers, the focus of their training is different than pilot training. The objective of their training is to allow them to better manage situations in which TCAS RA occur by understanding the functionality of TCAS II and how it works, how pilots are expected to use the system, and the potential interactions between TCAS and the ATC system.

Reporting and Monitoring

Flight Data Monitoring (FDM)

One way to improve operational safety and efficiency is through a pro-active non-punitive use of digital flight data from routine operations; by providing greater insight into the total flight operations environment. The best potential source of operational data is the operators' own Flight Data Monitoring (FDM), Flight Data Analysis (FDA), or Flight Operations Quality Assurance (FOQA) programs. The aim of this program is to improve safety through an analysis of information downloaded from an aircraft's on-board computer at the end of every flight. This information can be used by the operator to identify and discover underlying issues that have the potential to negatively affect safety and to allow operators to take appropriate action.

FDM programs generally involve systems that capture flight data, transform the data into an appropriate format for analysis, and generate reports and visualization to assist in assessing the data. The following capabilities are required for an effective FDM program:

- An on-board device to capture a wide range of in-flight parameters and record data on those parameters using flight data recorders (FDR);
- A means to transfer the data recorded on board the aircraft to a ground-based computer system;
- A means for the ground-based computer system to analyse the data, identify deviations from expected performance, generate reports to assist in interpreting the reports; and
- An optional software for a flight animation capability to integrate all data, presenting them as a simulation of in-flight conditions, thereby facilitating visualization of actual events;
- On some aircraft, dedicated TCAS recorders provide accurate information which can be added or matched to the FDR data should more detailed information be needed for a particular investigation.

IATA encourages operators to produce a set of standardized FDM safety measures and precursors related to potential mid-air collisions, such as TCAS RA alert/warning (genuine, nuisance or false).

Analysis and Trends of FDM data

FDM is an essential part of a well-functioning Safety Management System (SMS) for an aircraft operator, and it acts as one of the main data sources for monitoring the operational safety level. As indicated in the previous section, FDM is a powerful tool for the proactive hazard identification and risk assessment, it allows operators to verify standards and training programs and validate corrective actions. TCAS related safety indicators, the frequency of TCAS events, location, altitude, and performance are regularly monitored by operators, states, ANSPs, and other organizations through FDM and other monitoring programs, including pilot and controller reports, aircraft recorded data, Mode S RA downlink, ATC Radar Data.

It should be considered how these monitoring programs data sources are used and analysed by either the aircraft operators, the State, ANSPs or other organizations in order to mitigate hazards and apply adequate measures for safety improvement.

Aircraft operators can monitor the frequency of RAs as well as the quality of pilot responses to RAs, using FDM, FDRs, and dedicated TCAS recorders. When it comes to FDM, it is necessary for the FDR data to be transferred to the analysis platform. Various methods are available for downloading flight data to the analysis platform or offset for third party analysis. The data analysis system should have the following capabilities:

- The ability to display detailed information such as where, when, and what;
- The ability to display information in a logical and user-friendly way;
- The ability to program a range of alert detection thresholds to generate events when parameters exceed present values;
- The ability to enable detailed analysis of flight data;
- The ability to provide long term trend analysis of events.

Most FDM systems have the ability to record TCAS RAs. This means that data can depict an indication of whether a TCAS RA was issued, its duration and the type of RA (e.g. Climb, Descend, Level Off, etc.).

Alert detection thresholds are set in FDM to generate events when the value of the parameter exceeds a predetermined level or threshold. Exceedance detection is used to identify and assess operational risks as well as it draws the attention of the data analyst. Alert detection thresholds are set to generate events for trending or aggregating over a period of time and to enable pilots to be alerted to their own events. They are tailored to SOPs, aircraft type as well as specific operating scenarios. For example, an action taken by the pilot in response to the TCAS RA. Typically, most operators require that the pilots disengage the Auto-Pilot (AP) and follow the instruction of the TCAS RA while informing the ATC. The operator can easily cross check if the action taken by the flight crew is in compliance with their manuals or deviates from aircraft flight manual limits and standard operating procedures.

Analysis of Flight Data Exchange and Animation

The data in this section is extracted from the IATA's Flight Data eXchange (FDX) program. FDX is an aggregated de-identified database of FDA/FOQA type events that allows IATA to identify commercial flight safety issues which may not be visible to an airline with a dataset limited to their own operations. FOQA is the proactive use of recorded flight data from routine operations to improve aviation safety.

FDX allows Operators to identify flight safety issues by querying a shared, de-identified, database holding a wide range of safety measurements. Below are some examples of the analysis conducted from the aggregated de-identified FDX event data on TCAS RA. The data, which excluded corporate jets, included a total of 2,434 events that corresponded to TCAS RA triggered on board since January 2017 to October 2021. Figure 4 illustrates the MAC / TCAS RA trend rate of the participating airlines in FDX program.

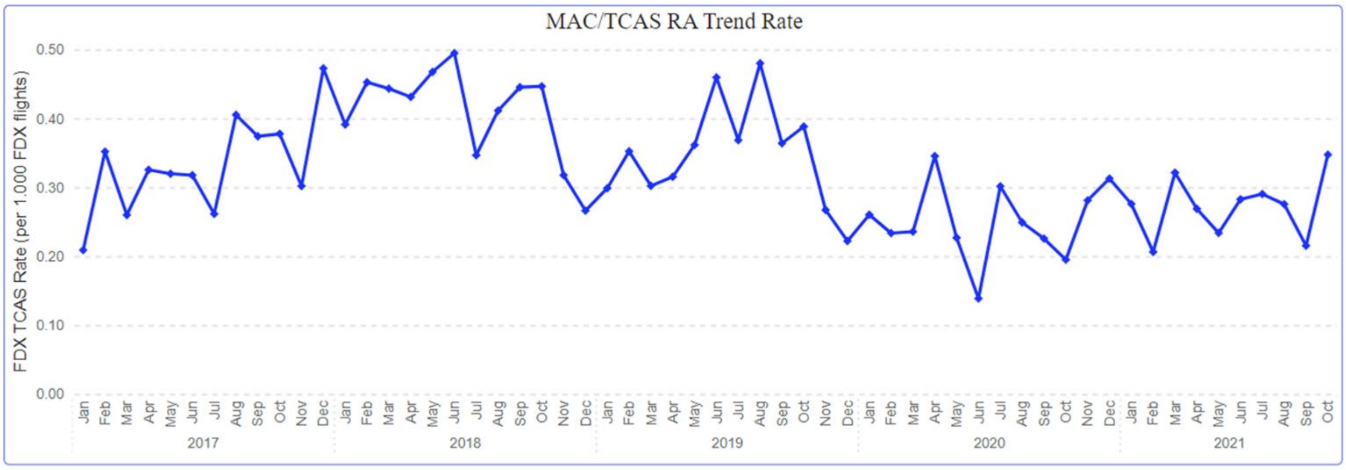


Figure 4: MAC / TCAS RA trend rate of the FDX participating airlines

Figure 5 presents the altitude bands within the TCAS RA events occurred. As can be seen, the highest event rate of events occurred above 10,000 feet. The rate calculated was 0.180 per 1,000 flights.

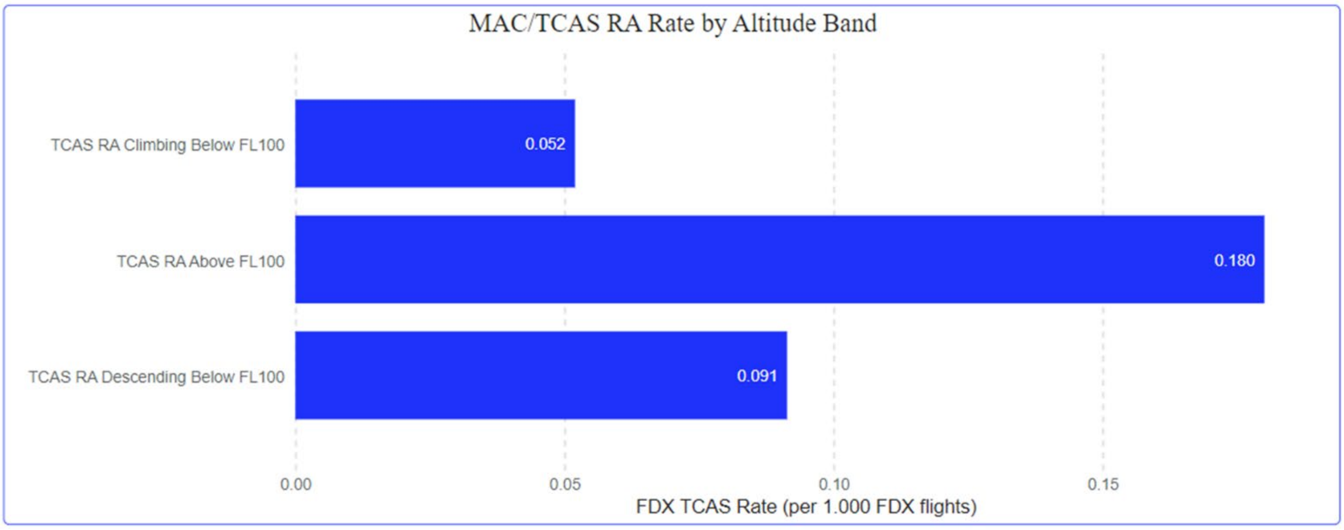


Figure 5: TCAS RA Occurred by Altitude Band

Notes: Figures 4 and 5 exclude Aircraft Category, Corporate Jets

Flight data animation is another component of a FOQA program. Animations are typically used to visualize an aircraft's flight profile, cockpit instrumentation, terrain, and scenario data.

There are three examples of animations here on TCAS RA. The first one is extracted from FDX Global Animation Archive and the other two are provided courtesy of SKYbrary. To view the animation in Figure 6, please click on the icon located on top right corner of figure 6. Note, This animation is without sound.

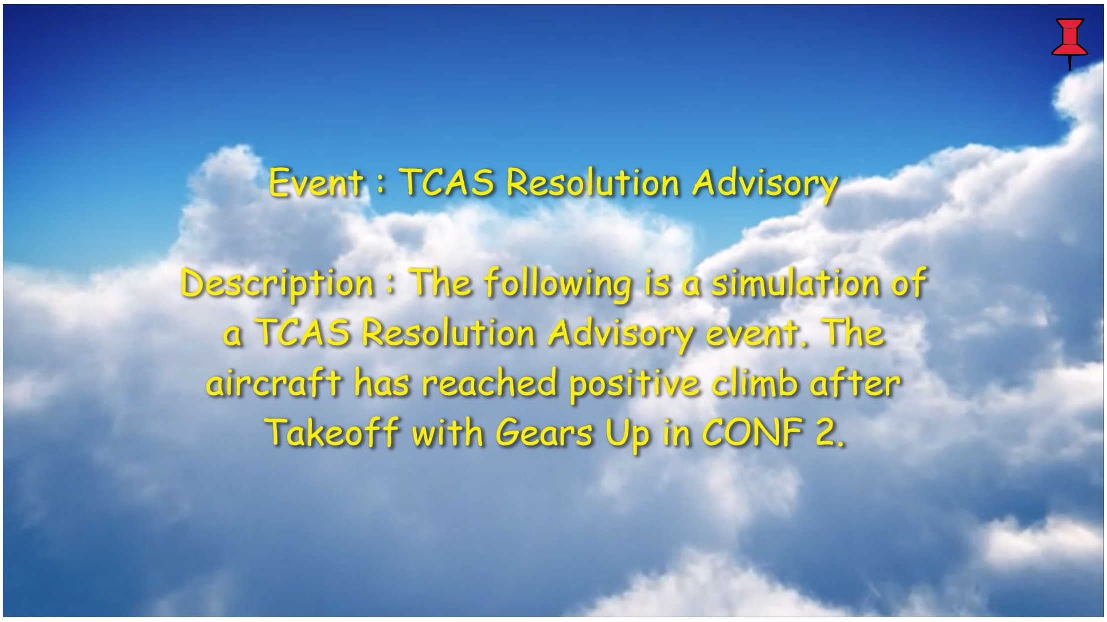


Figure 6: Animation _ TCAS RA Source IATA GADM

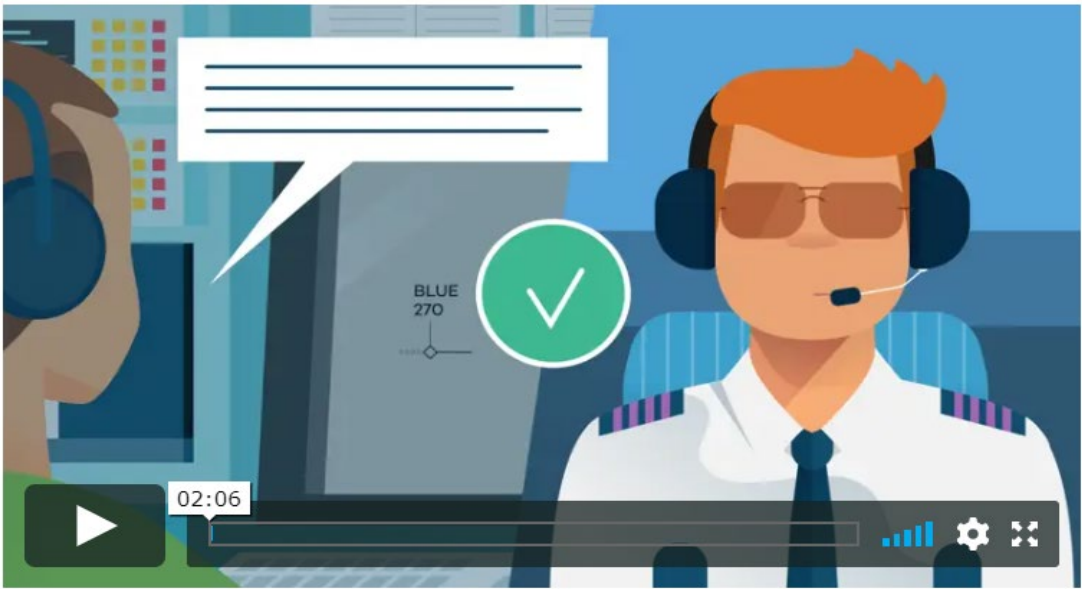


Figure 7: Animation _ TCAS RA Source SKYbrary

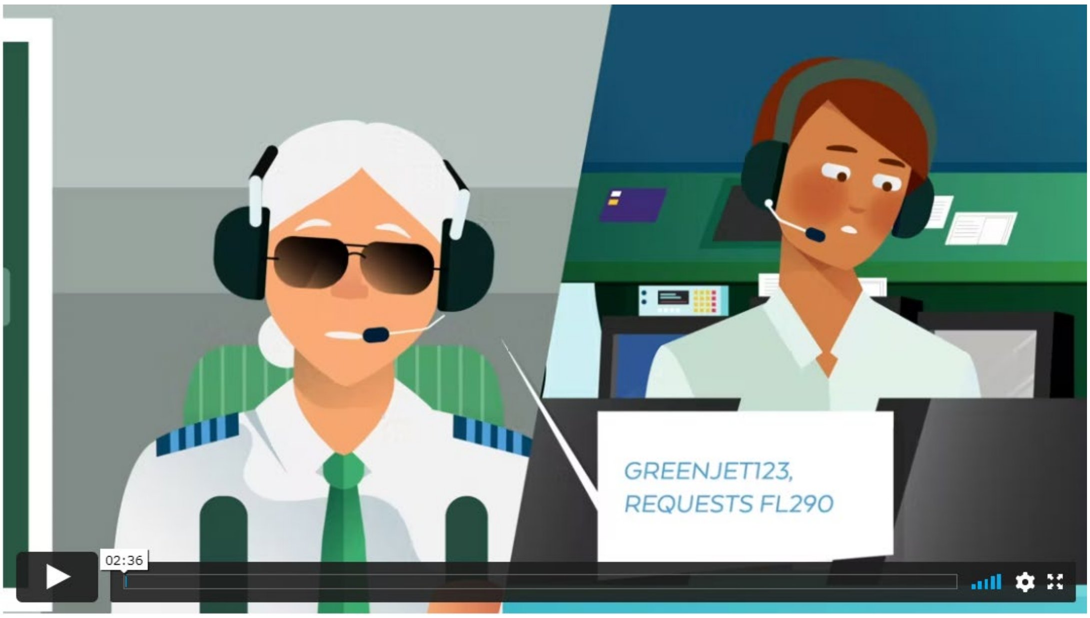


Figure 8: Animation _ TCAS RA Not Followed Source SKYbrary

TCAS Monitoring

TCAS monitoring programs should periodically publish findings from their analysis of TCAS events. The results of these analyses typically discuss technical and operational issues related to the use and operation of TCAS. Recurrent training programs should also address the results of the findings in both the academic and simulator portions of recurrent training sessions.

Opposite Initial Pilot Response (OIPR)

During the monitoring of TCAS II version 7.0 performance, it was discovered that in several cases pilots reacted to RAs in the opposite vertical sense than required, e.g. initiating a climb while a descent was needed. In most of these cases, the pilots corrected their actions within seconds and subsequently flew the RA in the correct vertical sense. The Initial Opposite Reactions (OIPR) were occurring across a wide range of aircraft types and operators. The OIPR events may diminish the effectiveness of collision avoidance advice given by TCAS or trigger excessive reactions to correct the RA sense.

Excessive g-loads while responding to RAs

Occasionally, pilots apply excessive g-loads while responding to RAs. These cases should be captured by RA monitoring and investigated, as excessive g-loads carry a risk of injury to the aircraft occupants and, in some cases, damage to the aircraft.

Responses to TAs

Occasionally, pilots react to TAs, contrary to the operating procedures, by initiating a turn, changing vertical rates, or otherwise not complying the current ATC instruction or clearance. Cases have been reported when responses to TAs caused a reduction of separation or induced a conflict with a third-party aircraft. These cases should be captured by RA monitoring and investigated.

Since it will not always be possible to detect the OIPR using the criteria outlined above in Tables 1 and 2, it is recommended that the operators monitor the FDM data for OIPR events to address them accordingly. The OIPRs may be a symptom of a training or operational issue.

Example of TCAS RA not followed Incident

Description

On 14 October 2016, a DHC-8-402 aircraft was conducting an instrument flight rules flight within Canada to Sudbury Airport, Ontario, an uncontrolled airport. This flight was inbounding to Sudbury Airport from the south, with a clearance for a visual approach. A DHC-8-402 aircraft, which was also conducting an instrument flight rules flight, had taken off from Sudbury Airport under visual flight rules and was heading south. At 10:02:21 Eastern Daylight Time, when both aircraft were about 9.5 nautical miles southwest of Sudbury Airport, at approximately 4000 feet above sea level, both flight crews received a resolution advisory from their respective traffic alert and collision avoidance systems. Surveillance data indicated that the two aircraft came within 0.4 nautical miles of each other at the same altitude. The Investigation noted that the conflict had occurred in Class 'E' airspace after the departing aircraft had cancelled Instrument Flight Rule (IFR) to avoid a departure delay attributable to the inbound IFR aircraft.

Some of the findings and risks

One of the involved operators did not have SOPs for the selection of the TCAS continuous and automatic modes. During the occurrence, the Captain's traffic display was still in default automatic mode and, as a result, the Captain did not have a complete understanding of the other aircraft position and altitude.

Following the TCAS resolution advisory (RA), one of the aircraft captains manoeuvred the aircraft contrary to the RA instructions. Although permitted by company SOPs, this alternate manoeuvre reduced the vertical separation between the 2 aircraft.

Simulator training syllabus and scripts of one of the operators did not address RA commands other than climb and descend and their associated reversals. As a result, the Captain was likely inexperienced in the initial RA instruction to maintain vertical speed, and manoeuvred contrary to the command, which reduced the vertical separation between the two aircraft.

Furthermore, the pilots did not report their responses to the TCAS RA as such, ATC personnel were unaware of the severity of the occurrence and did not contact the investigation authority immediately. As a result, the cockpit voice recorders were not quarantined in a timely manner and the data was overwritten.

The SOPs of both aircraft require the PM to communicate with ATC during a TCAS RA event. However, both airlines stipulate TCAS phraseology that differs from their SOPs.

References

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- EUROCONTROL Operational Safety Study: TCAS RA not Followed
- The Assessment of Pilot Compliance with TCAS RAs, TCAS Mode Selection and Serviceability Using ATC Radar Data, EUROCONTROL, 2nd ed., 9 April 2021
- ICAO Annex 6 – Operation of Aircraft - Part I - International Commercial Air Transport – Aeroplanes (Eleventh edition – 2108, data applicable: 8 November 2018).
- ICAO Annex 10 – Aeronautical Telecommunications - Volume IV - Surveillance Radar and Collision Avoidance Systems (Fifth edition – 2014 amendment 90, date applicable: 8 November 2018).
- ICAO Doc. 8168 – PANS-OPS – Procedures for Air Navigation Services – Aircraft Operations - Volume III - Flight Procedures (First edition – 2018).
- ICAO Doc. 9863 – Airborne Collision Avoidance System (ACAS) Manual (Third edition – 2021).
- EUROCONTROL ACAS Guide – Airborne Collision Avoidance. December 2021.
- RTCA DO-185B – Minimum Operational Performance Standards (MOPS) for Traffic Alert and Collision Avoidance System (TCAS II) Airborne Equipment.
- RTCA DO-385 – Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS X) (ACAS Xa and ACAS Xo).
- EUROCAE ED-143 – Minimum Operational Performance Standards (MOPS) for Traffic Alert and Collision Avoidance System II (TCAS II).
- EUROCAE ED-256 – Minimum Operational Performance Standards for Airborne Collision Avoidance System X (ACAS X) (ACAS Xa and ACAS Xo).
- EUROCAE ED-224 – Minimum Aviation System Performance Specification (MASPS) for Flight Guidance System (FGS) coupled to ACAS.
- FAA AC 20-151C (Advisory Circular) – Airworthiness Approval of Traffic Alert and Collision Avoidance Systems (TCAS II), Versions 7.0 & 7.1 and Associated Mode S Transponders.

APPENDIX A: Future of Collision Avoidance: ACAS X

The Federal Aviation Administration (FAA) has been funding research and development of a new approach to airborne collision avoidance (known as ACAS X) since 2008. This approach uses 'dynamic programming' and other computer science techniques (which were not available when TCAS II was first developed) to generate alerts using an off-line optimization of resolution advisories.

ACAS X Principles

Instead of using a set of hard-coded rules, ACAS X alerting logic is based upon a numeric lookup table optimised with respect to a probabilistic model of the airspace and a set of safety and operational considerations.

The ACAS X probabilistic model provides a statistical representation of the aircraft position in the future. It also takes into account the safety and operational objectives of the system enabling the logic to be tailored to particular procedures or airspace configurations.

This is fed into an optimisation process called "dynamic programming" to determine the best course of action to follow according to the context of the conflict. This employs a rewards versus costs system to determine which action would generate the greatest benefits (i.e. maintain a safe separation while implementing a cost-effective avoidance manoeuvre). Key metrics for operational suitability and pilot acceptability include minimizing the frequency of alerts that result in reversals/intentional intruder altitude crossings or disruptive advisories in non-critical encounters.

The look-up table is used in real-time on-board the aircraft to resolve conflicts. ACAS X collects surveillance measurements from an array of sources (approximately every second). Various models are used (e.g. a probabilistic sensor model accounting for sensor error characteristics) to estimate a state distribution, which is a probability distribution over the current positions and velocities of the aircraft. The state distribution determines where to look in the numeric lookup table to determine the best action to take (which includes the option 'do nothing'). If deemed necessary, resolution advisories are then issued to the pilots.

ACAS X Benefits

The following benefits are foreseen through the introduction of ACAS X:

- Reduction of 'unnecessary' advisories: TCAS II is an effective system operating as designed, but it can issue alerts in situations where aircraft will remain safely separated.
- Adaptability to future operational concepts: Both SESAR and NextGen plan to implement new operational concepts which will reduce the spacing between aircraft. TCAS II in its cur- rent form is not compatible with such concepts and would alert too frequently to be useful.
- Extending collision avoidance to other classes of aircraft: To ensure advisories can be followed, TCAS II is restricted to categories of aircraft capable of achieving specified performance criteria (e.g. aircraft must be able to achieve a rate of climb of 2500 ft/min.), which excludes many General Aviation (GA) and Unmanned Aircraft Systems (UAS) or Remotely Piloted Aircraft Systems (RPAS).
- Use of future surveillance environment: Both SESAR and NextGen make extensive use of new surveillance sources, especially satellite-based navigation and advanced ADS-B functionality. TCAS II however relies solely on transponders on-board aircraft which will limit its flexibility to incorporate these advances.
- Safety improvement: It is envisaged that ACAS X will provide an improvement in safety while reducing the unnecessary alert rate.

APPENDIX B: Assessment of pilot compliance with TCAS RA using ATC radar data.

This section is provided by EUROCONTROL without contribution from IATA

The full report containing statistical results of the pilot compliance with TCAS RA can be found on SKYbrary, (click here). Any subsequent updates and revisions will be available under the same SKYbrary link.

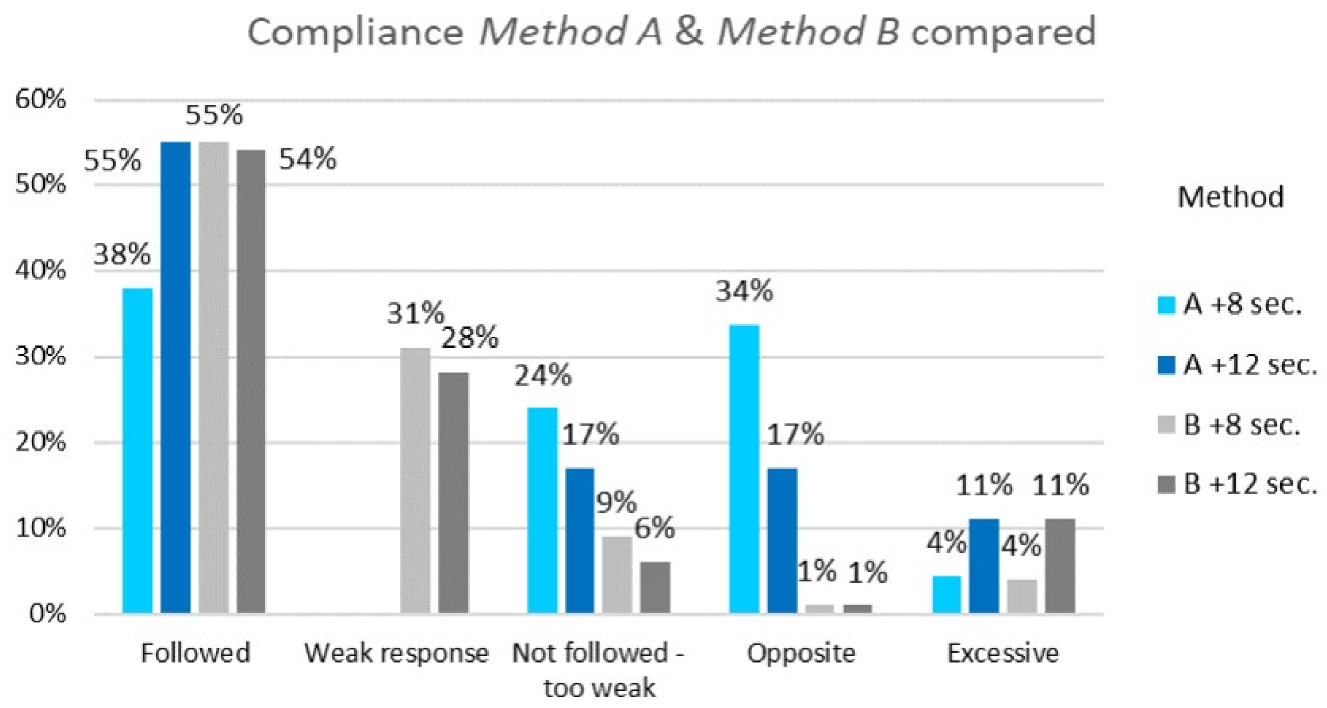
This report available on SKYbrary contains Method B algorithm (in Annex 1). For non-algorithmic description of Method B refer to Appendix C to this Guidance Material.

Assessment of pilot compliance with TCAS RA using ATC radar data – summary

EUROCONTROL study of pilot compliance with TCAS RA concluded that a significant proportion of RAs are not flown correctly. This conclusion was drawn using either assessment method (Method A or Method B).

In summary, the overall compliance rates using the two methods are (see figure below):

- Method A, at 8 seconds: 38%
- Method A, at 12 seconds: 55%
- Method B, at 8 seconds: 55%
- Method B, at 12 seconds: 54%



Method B also detects 'weak compliance' – these are aircraft manoeuvring in the required vertical direction, but not quickly enough or with insufficient rate. Under the Method B scheme, a further 31% of pilots are weakly following the RA at 8 seconds and 28% at 12 seconds after the RA is triggered. These results are line with anecdotal evidence from various sources. The study was not well placed to determine directly whether safety is degraded when pilots do not follow RAs correctly. However, it can be assumed that any incorrect responses to RAs may fail to resolve a collision risk (as indicated by simulations of TCAS in safety studies).

The study found as number of cases where, in the absence of correct pilot response, vertical separation at the Closest Point of Approach was significantly reduced. However, the relative infrequency of these cases meant they could not be used to draw statistically significant conclusions. Moreover, the achieved vertical separation was affected by additional factors, including: pilot responses to modified RAs; manoeuvres of the other aircraft in the encounter; and, in the case of Level Off RAs (which are typically issued when the aircraft are still separated) any degradation of separation is difficult to detect.

For more information refer to full report on SKYbrary.

APPENDIX C: Method B description

This section is provided by EUROCONTROL without contribution from IATA

1. Introduction

1.1. Background

The Method B RA compliance evaluation scheme assesses to what extent the pilot reaction to an RA[2] complies with the required vertical rate. As well as just the vertical rate required by the RA, the scheme also takes account of the fact that if a change in the aircraft's vertical rate is required this will not be achieved instantaneously; but rather will require a period of acceleration before the required vertical rate is achieved.

An ideal response, based on the Standard Pilot Model of the ACAS SARPs, is calculated (and depends on the time of evaluation relative to the time at which the RA was issued). If the required vertical rate has not been achieved then the actual vertical rate achieved is compared to the ideal response, to assess the level of compliance.

1.2. Standard Pilot Model

The Standard Pilot Model assumes that the pilot will continue with his current vertical rate for a delay period before he reacts to the RA: for an initial RA this delay is assumed to be 5 seconds; for any change in RA strength or sense this delay is assumed to be 2.5 seconds.

If the RA requires a change in vertical rate then the Standard Pilot Model assumes that the pilot will move towards the required vertical rate with a fixed vertical acceleration: for an increase rate or reversal RA this acceleration is assumed to be 0.35*g*;[3] for other corrective RAs the acceleration is assumed to be 0.25*g*.

2. Evaluation

2.1. Categories

The scheme assigns one of up to five categories to the pilot response:

For **Corrective RAs** (*i.e.* those requiring a change in vertical rate: displayed on an IVSI with a red arc indicating prohibited vertical rates; and a green arc indicating required vertical rates) the categories are:

- '**Excessive response**' – the pilot responds in the correct sense but with a vertical rate beyond that required by the RA;
- '**Following**' – the pilot responds as required by the RA;
- '**Weak response**' – the pilot responds in the correct sense but with a vertical rate that falls short of the required rate';
- '**No response**' – the pilot makes little or no change to his vertical rate;
- '**Opposite response**' – the pilot responds in a direction opposite to that required by the RA.

[2] **Single sense RA only: dual sense RAs which can occur when there is more than one threat aircraft, are beyond the scope of this analysis.**

[3] ***g* is the acceleration due to gravity which has a conventional value of 1930.4 fpm/s.**

For **Preventive RAs** (*i.e.* those not requiring a change in vertical rate: displayed on an IVSI with a red arc indicating prohibited vertical rates) only two of these categories are applicable:

- '**Following**' – the pilot avoids the vertical rates prohibited by the RA;
- '**Opposite response**' – the pilot does not avoid the vertical rates prohibited by the RA.

The algorithms used to assign these categories are described in the next sections. The algorithms for upward sense RA and downward sense RAs are the converse of each other, but for clarity are each described separately and completely. *N.B.* climb rates have positive values, and descent rates have negative values.

2.2. Upward Sense

In this analysis $\boldsymbol{V_t}$ is the vertical rate achieved at the point of evaluation, which is some short time, $\boldsymbol{t}$, after the RA was issued.

2.2.1. Preventive RA (Upward sense)

The upper limit of the prohibited vertical rates (the red arc) is $\boldsymbol{R}$. Since this is a preventive upward sense RA, the vertical rate at the time of the RA will be above the limit of the prohibited rates. A threshold for compliance with the RA is defined close to the limit of the red arc but with a margin of 300 fpm below; *i.e.* at **$\boldsymbol{R}$ – 300 fpm**.

If the achieved vertical rate is equal to this threshold or climbing faster then the RA is being followed:

Following: $V_t \geq R - 300$ fpm

Otherwise, the response is opposite to the RA:

Opposite response: $V_t < R - 300$ fpm

2.2.2. Corrective RA (Upward sense)

The upper limit of the prohibited vertical rates (the red arc) is $\boldsymbol{R}$. This is also the lower limit of the required vertical rate (the green arc) which extends upward to $\boldsymbol{G}$. A threshold for compliance with the RA is defined close to the limit of the red arc but with a margin of 300 fpm below; *i.e.* a lower static threshold at **$\boldsymbol{R}$ – 300 fpm**. A threshold for excessive response is defined at 200 fpm beyond the limit of the green arc; *i.e.* an upper static threshold at **$\boldsymbol{G}$ + 200 fpm**.

If the achieved vertical rate is climbing faster than the upper static threshold then the response to the RA is excessive:

Excessive response: $V_t > G + 200$ fpm

Otherwise, if the achieved vertical rate is climbing faster than the lower static threshold then the RA is being followed:

Following: $V_t > R - 300$ fpm

If the achieved vertical rate is climbing slower than the lower static threshold (or descending) then the compliance category needs to be determined by comparing the achieved vertical rate with dynamic thresholds. These dynamic thresholds are based on the achievable vertical rate, calculated from the vertical rate of the aircraft at the time the RA was issued, $\boldsymbol{V_0}$, and time that has elapsed since the RA was issued, $\boldsymbol{t}$.

The achievable vertical rate, $\boldsymbol{A}$, is calculated thus:

- if the elapsed time is not greater than the reaction time, τ, the achievable vertical rate is equal to the vertical rate at the time of the RA;
- if the elapsed time is greater than the reaction time, the achievable vertical rate is equal to the vertical rate at the time of the RA augmented by the change in vertical rate during a phase with upward acceleration at $\boldsymbol{ng}$.

$$A = V_0 + ng \times \max(0, t - \tau)$$

A target vertical rate, ***T***, is calculated as the lower of the achievable vertical rate and the required vertical rate, together with a margin of 300 fpm:

$$T = \min(A, R) - 300 \text{ fpm}$$

If the achieved vertical rate is climbing faster than the target rate then the RA is being followed:

Following: $V_t > T$

Otherwise, if the achieved vertical rate is not climbing as fast as the target rate but has changed by at least 300 fpm in the correct sense then the RA is being weakly followed:

Weak response: $V_t > V_0 + 300$ fpm

Otherwise, if the achieved vertical rate is within 300 fpm of the vertical rate at the time of the RA then the RA is not being followed:

No response: $V_t \geq V_0 - 300$ fpm

Otherwise, if the achieved vertical rate is more than 300 fpm away, in the opposite direction, from the vertical rate at the time of the RA, then the response is opposite to the RA:

Opposite response: $V_t < V_0 - 300$ fpm

2.3. Downward Sense

In this analysis $\boldsymbol{V_t}$ is the vertical rate achieved at the point of evaluation, which is some short time, ***t***, after the RA was issued.

2.3.1. Preventive RA (Downward sense)

The lower limit of the prohibited vertical rates (the red arc) is ***R***. Since this is a preventive downward sense RA, the vertical rate at the time of the RA will be below the limit of the prohibited rates. A threshold for compliance with the RA is defined close to the limit of the red arc but with a margin of 300 fpm above; *i.e.* at ***R* + 300 fpm**.

If the achieved vertical rate is equal to this threshold or descending faster then the RA is being followed:

Following: $V_t \leq R + 300$ fpm

Otherwise, the response is opposite to the RA:

Opposite response: $V_t > R + 300$ fpm

2.3.2. Corrective RA (Downward sense)

The lower limit of the prohibited vertical rates (the red arc) is ***R***. This is also the upper limit of the required vertical rate (the green arc) which extends downward to ***G***. A threshold for compliance with the RA is defined close to the limit of the red arc but with a margin of 300 fpm above; *i.e.* an upper static threshold at ***R* + 300 fpm**. A threshold for excessive response is defined at 200 fpm beyond the limit of the green arc; *i.e.* a lower static threshold at ***G* – 200 fpm**.

If the achieved vertical rate is descending faster than the lower static threshold then the response to the RA is excessive:

Excessive response: $V_t < G - 200$ fpm

Otherwise, if the achieved vertical rate is descending faster than the upper static threshold then the RA is being followed:

Following: $V_t < R + 300$ fpm

If the achieved vertical rate is descending slower than the lower static threshold (or climbing) then the compliance category needs to be determined by comparing the achieved vertical rate with dynamic thresholds. These dynamic thresholds are based on the achievable vertical rate, calculated from the vertical rate of the aircraft at the time the RA was issued, $\boldsymbol{V_0}$, and time that has elapsed since the RA was issued, ***t***.

The achievable vertical rate, ***A***, is calculated thus:

- if the elapsed time is not greater than the reaction time, τ, the achievable vertical rate is equal to the vertical rate at the time of the RA;
- if the elapsed time is greater than the reaction time, the achievable vertical rate is equal to the vertical rate at the time of the RA augmented by the change in vertical rate during a phase with downward acceleration at ***ng***.

$$A = V_0 - ng \times \max(0, t - \tau)$$

A target vertical rate, ***T***, is calculated as the higher of the achievable vertical rate and the required vertical rate, together with a margin of 300 fpm:

$$T = \max(A, R) + 300 \text{ fpm}$$

If the achieved vertical rate is descending faster than the target rate then the RA is being followed:

Following: $V_t < T$

Otherwise, if the achieved vertical rate is not descending as fast as the target rate but has changed by at least 300 fpm in the correct sense then the RA is being weakly followed:

Weak response: $V_t < V_0 - 300$ fpm

Otherwise, if the achieved vertical rate is within 300 fpm of the vertical rate at the time of the RA then the RA is not being followed:

No response: $V_t \leq V_0 + 300$ fpm

Otherwise, if the achieved vertical rate is more than 300 fpm away, in the opposite direction, from the vertical rate at the time of the RA, then the response is opposite to the RA:

Opposite response: $V_t > V_0 + 300$ fpm

APPENDIX D: RA Compliance MS-Excel Tool User Guide

This section is provided by EUROCONTROL without contribution from IATA

To access the RA Compliance Tool, please click here or the file can be requested via email from EUROCONTROL at acas@eurocontrol.int Please note that the file contains macros (without macros it will not be usable). So please download and save the file on your computer, Enable Editing, and then Enable Content.

1. Introduction

1.1. The RA Compliance Tool is a Microsoft® Excel® Workbook that allows a user to assess the extent to which a pilot, who receives a single-sense[4] ACAS RA, has responded (by constraining or changing the aircraft's vertical speed) in a standard manner.

1.2. For a specific RA the user indicates whether it is:

- an initial RA; or a subsequent RA;

and provides:

- the version of ACAS (TCAS Version 7.0; TCAS Version 7.1; or ACAS X_A);
- the vertical sense of the RA ("Upward"; or "Downward");
- the strength of the RA (from a drop-down list);
- the vertical rate of the aircraft when the RA was issued (in fpm);

and, for "Maintain Vertical Speed" RAs:

- the vertical speed required by the RA (in fpm).

1.3. For the evaluation the user supplies:

- the time after the RA at which the evaluation is required (in seconds); and
- the vertical rate of the aircraft at this time (in fpm);

1.4. Given the above details, the tool evaluates the compliance of the vertical rate achieved, by using two methods:

- **Method A** simply compares the achieved vertical rate with the required vertical rate – this method is independent of the time of evaluation and is detailed in [1];
- **Method B** is more sophisticated and takes account of the fact that an acceleration phase, after a nominal response delay and at a nominal acceleration, is expected before the required vertical rate is achieved. This method is detailed in [2].

[4] Dual-sense RAs (in which both climb and descent rates are simultaneously constrained) can occur if there is more than one collision threat, but are beyond the scope of the tool.

1.5. The nominal response delay and nominal acceleration constitute the "standard pilot response" which is implicit in the collision avoidance algorithms and is detailed in the ACAS SARPs (section 4.4.2.5 of [3]):

- for an initial corrective RA, the pilot is assumed to initiate a response to the RA after a delay of 5s and to accelerate the aircraft to the required vertical rate with an acceleration of 0.25*g*;
- for a subsequent corrective RA, the pilot is assumed to initiate a response to the changed RA after a delay of 2.5s and to accelerate the aircraft to the required vertical rate with either:
    - an acceleration of 0.25*g*, for 'normal' RAs; or
    - an acceleration of 0.35*g*, for 'exigent' RAs ('reverse-rate' RAs and 'increase-rate' RAs).
- The value of *g* (the acceleration due to gravity) is taken as 9.80665 m/s (= 32.174 ft/s^2 = 1920.4 fpm/s) as per the ICAO standard atmosphere model [4].

2. Getting started

2.1. The tool is an Excel workbook with macros and the current version of the tool is "RA_compliance_tool_v1.0.xlsm".

2.2. As the tool contain macros, it must be saved on a local drive in order to be used (*i.e.* it cannot be run from an email attachment).

2.3. Locate the tool and open it as an Excel file in the normal manner. If prompted, enable content so that the VBA macros can run.

Figure 1). The "Limitations of Use / Disclaimer" page can be viewed at any time by selecting the 'Disclaimer' sheet tab at the bottom of the page.

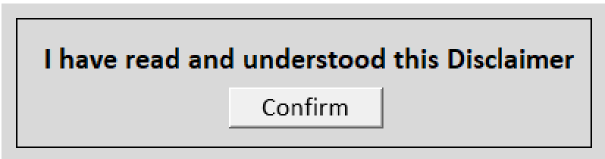


Figure 9: Confirmation button on the 'Disclaimer' sheet.

2.5. The tool will now display the 'User_input' sheet where the user can enter the details of the RA and the response that they wish to evaluate.

Figure 2).

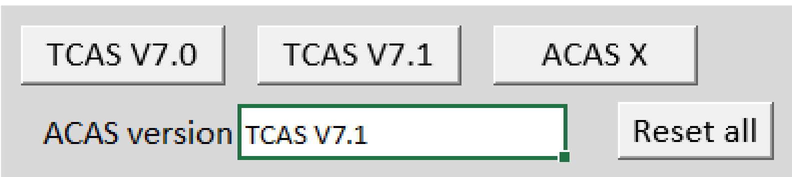


Figure 10: ACAS version selection buttons and Reset button.

2.7. While not necessary, it is recommended as good practice to start by clicking the “Reset all” button near the top of the sheet. This clears the numerical entries and sets selections to their default values, ready for the user to enter fresh details. The “Reset all” option can be used at any stage, should the user wish to return the tool to its initial state.

2.8. Select the relevant version of ACAS by clicking on either the “TCAS V7.0”, “TCAS V7.1”, or “ACAS X” button; the version selected appears in the “ACAS version” cell beneath.

3. RA details

3.1. Below the version selection area are two large boxes (one above the other) for the analysis of Initial RAs (see Figure 3) and/or Subsequent RAs (see Figure 4) respectively:

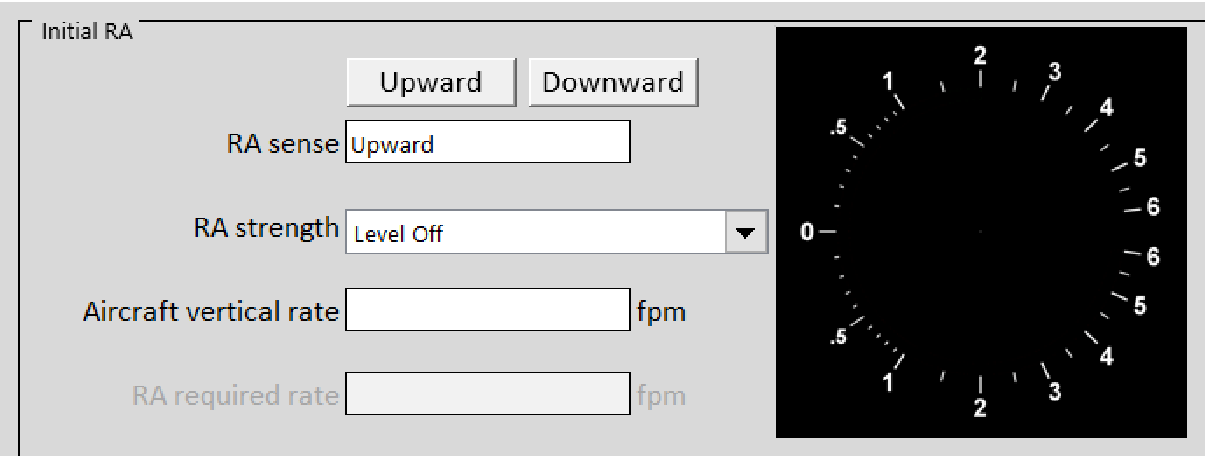


Figure 11: Initial RA details entry space.

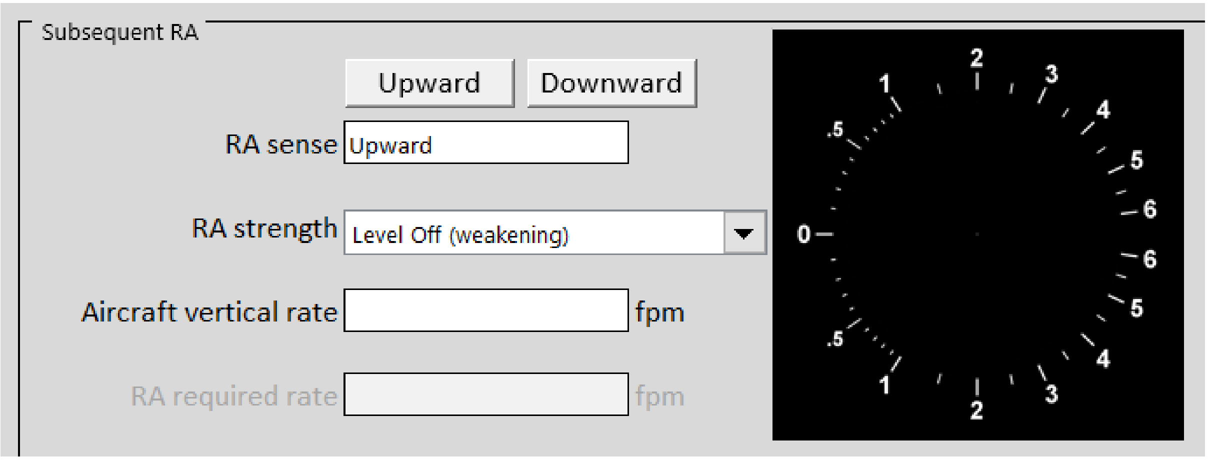


Figure 12: Subsequent RA details entry space.

3.2. Within each analysis box are buttons and data entry cells for details of the RA; a representation of an IVSI RA display; two function buttons; and beneath these three Evaluation boxes (the latter being described in section 4).

3.3. In the appropriate analysis box, select the sense of the RA by clicking the “Upward” or “Downward” button. The selected sense appears in the “RA sense” cell.

3.4. In the “RA strength” cell, select the RA strength from the drop-down list. The list contains only the RAs applicable to the type of collision avoidance system and the RA sense that the user has selected.

3.5. In the “Aircraft vertical rate” cell, enter the vertical rate of the aircraft at the time that the RA was generated, in feet per minute (this is the instant at which the RA was generated, for an Initial RA; the instant at which the RA sense/strength changed for a Subsequent RA). *N.B.* Enter a negative value for a descent rate (*i.e.* the number preceded by the minus sign “-”). For aircraft flying level the value “0” must be entered.

Figure 5). The red arc and (if any) green arc are shown on the IVSI and the corresponding aural annunciation is shown in text to the right. *N.B.* This is a generic representation of the RA display – the actual display on the aircraft might be on an IVSI, a vertical speed tape, and/or pitch cues on the PFD.

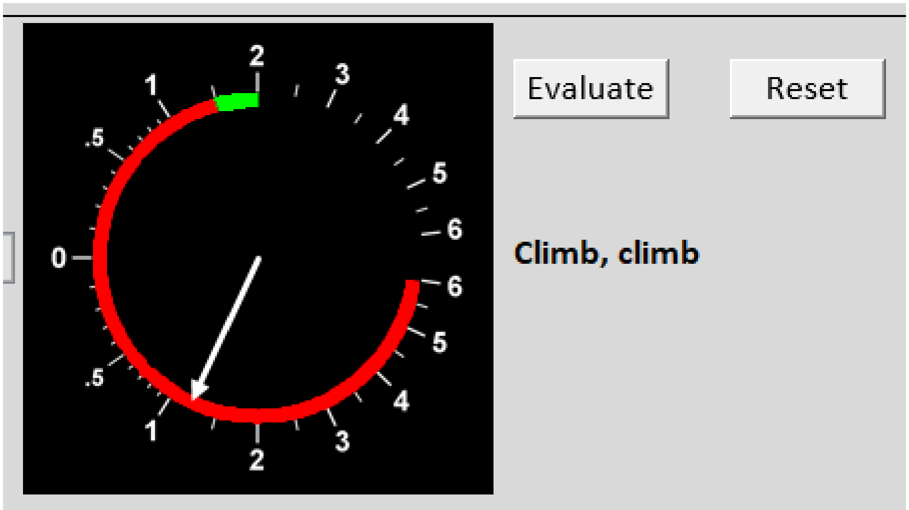


Figure 13: Representation of RA display on the IVSI.

3.7. If the selected RA strength is “Maintain Vertical Speed” or “Crossing Maintain Vertical Speed”, the “RA required rate” cell will become active and an additional user-supplied input is required (see Figure 6). Enter the vertical rate that was required by the RA in the cell.

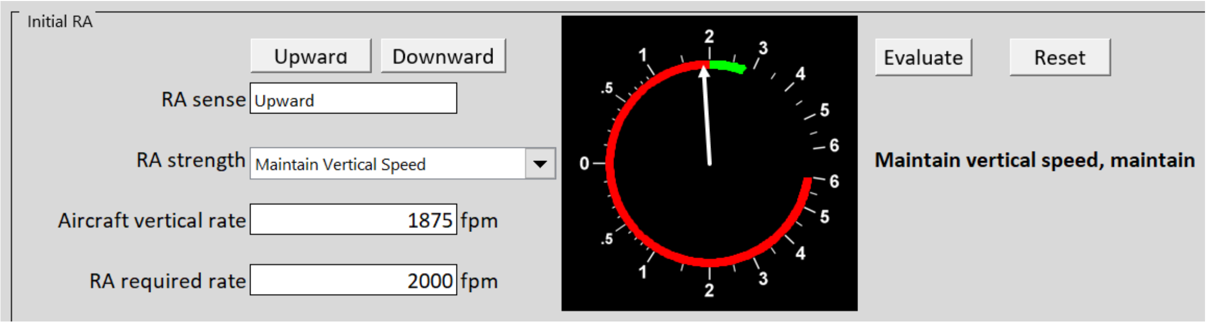


Figure 14: Data entry and RA display for a Maintain Vertical Speed RA.

Figure 7).

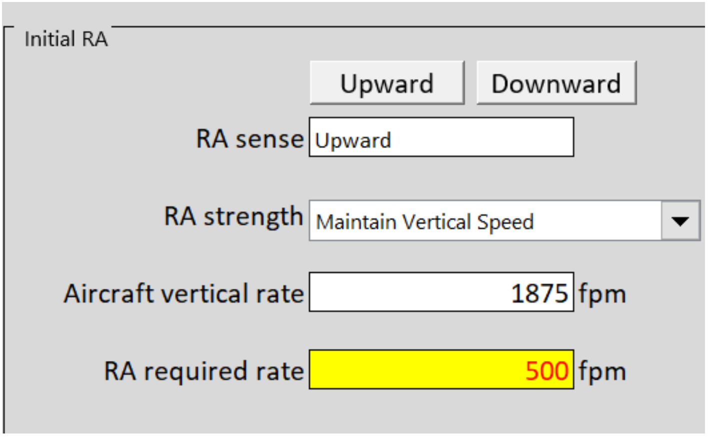


Figure 15: Inconsistent RA required rate highlighted for a Maintain Vertical Speed RA.

4. Compliance evaluation

Figure 8).

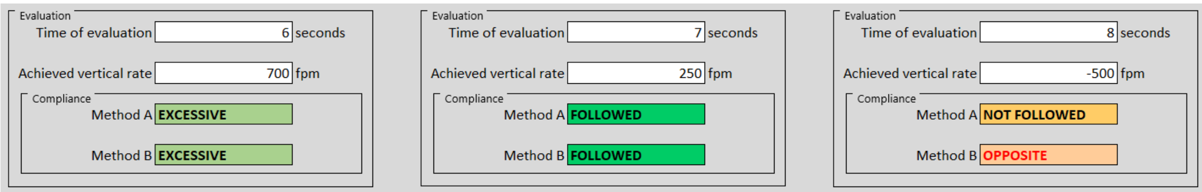


Figure 16: Evaluation of compliance with an RA at three separate instants.

4.2. Enter the “Time of evaluation” in one of the boxes. For an Initial RA, this is the time, in seconds, since the instant at which the RA was generated. For a Subsequent RA, this is the time, in seconds, since the instant at which the RA sense/strength changed (rather than since the instant at which the corresponding initial RA was generated).

4.3. Enter the “Achieved vertical rate” in the corresponding cell, in feet per minute. This is the vertical rate of the aircraft at the time of the evaluation. *N.B.* Enter a negative value for descent rates (*i.e.* the number preceded by the minus sign “-”). For aircraft flying level the value “0” must be entered.

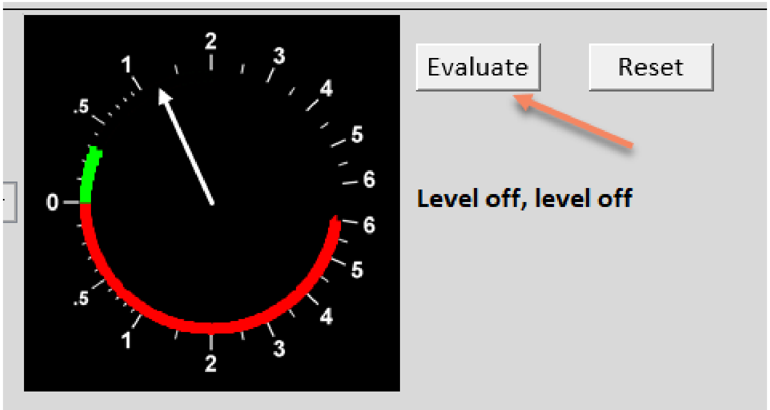


Figure 17: Evaluate button which, when clicked, calculates the compliance given the entered data.

4.5. To evaluate the compliance of the same RA but with different “Achieved vertical rate” and/or at a different “Time of evaluation”, enter the appropriate values in an unused “Evaluation” box; alternatively change the existing values in a used “Evaluation” box – in either case, then click the “Evaluate” button to determine the compliance (see Figure 9).

5. Trouble-shooting

5.1. RA display

5.1.1. No coloured arcs displayed – possible causes and solutions:

- Compliance has not yet been evaluated[5]
  - click “Evaluate” button.
- RA strength is blank
  - check version of ACAS and select a valid RA strength, then click “Evaluate” button.

5.1.2. Coloured arcs have non-standard appearance – possible causes and solutions:

- Glitch in Excel’s page display
  - change the magnification of the page using the slider at the bottom right of the Excel window.

5.1.3. No needle indicating aircraft vertical rate – possible causes and solutions:

- Compliance has not yet been evaluated
  - click “Evaluate” button.

[5] An occasional glitch in Excel means that you may have to click the “Evaluate” button twice.

- “Aircraft vertical rate” is blank
    - enter a value for the vertical rate (for aircraft flying level the value “0” must be entered), then click “Evaluate” button.
- “Aircraft vertical rate” is non-numeric
    - enter a number for the vertical rate (do not include units), then click “Evaluate” button.

5.2. Warnings

5.2.1. The tool checks for certain potential inconsistencies between the input values, and highlights these by shading the input cell yellow. This does not necessary mean that there is an error – rather that the combination of inputs was unexpected: if the inputs are correct, the tool will still give a valid evaluation.

5.2.2. “Aircraft vertical rate” is highlighted – possible causes and solutions:

- “RA strength” is blank
    - check version of ACAS and select a valid “RA strength”, then click “Evaluate” button.
- “Aircraft vertical rate” is non-numeric
    - enter a number for the vertical rate (do not include units), then click “Evaluate” button.
- “RA strength” is preventive but needle on IVSI is well into the red arc
    - check “RA strength” and “Aircraft vertical rate”, then click “Evaluate” button.
- “RA strength” is corrective but needle on IVSI is well away from the red arc
    - check “RA strength” and “Aircraft vertical rate”, then click “Evaluate” button.

5.2.3. “RA required rate” is greyed out – possible causes and solutions:

- “RA strength” is not “Maintain Vertical Speed” nor “Crossing Maintain Vertical Speed”
    - check “RA strength”, then click “Evaluate” button.

5.2.4. “RA required rate” is highlighted – possible causes and solutions:

- “RA required rate” is blank
    - enter a value for the required rate, then click “Evaluate” button.
- “RA required rate” is non-numeric
    - enter a number for the required rate (do not include units), then click “Evaluate” button.
- “Aircraft vertical rate” is blank
    - enter a value for the vertical rate (for aircraft flying level the value “0” must be entered), then click “Evaluate” button.
- “Aircraft vertical rate” and “RA required rate” differ significantly
    - check values of these variables, then click “Evaluate” button.

- Magnitude of “RA required rate” is less than 1500 fpm (in which case a ‘Climb’ or a ‘Descend’ RA is expected)
    - check strength of RA, check values of the required rate, then click “Evaluate” button.

5.2.5. “Time of evaluation” is highlighted – possible causes and solutions:

- “Time of evaluation” is non-numeric
    - enter a number for the required time (do not include units), then click “Evaluate” button.
- “Time of evaluation” is not greater than standard pilot model response delay (*viz*. 5s for Initial RAs; 2.5s for Subsequent RAs)
    - enter a value greater than standard pilot model response delay, then click “Evaluate” button.

5.2.6. “Achieved vertical rate” is highlighted – possible causes and solutions:

- “Achieved vertical rate” is blank
    - enter a value for the achieved rate (for aircraft flying level the value “0” must be entered), then click “Evaluate” button.
- “Achieved vertical rate” is non-numeric
    - enter a number for the vertical rate (do not include units), then click “Evaluate” button.

5.3. <u>Method A</u>

5.3.1. Method A evaluation is “NOT APPLICABLE” – possible causes and solutions:

- Compliance has not yet been evaluated
    - click the “Evaluate” button
- “Achieved vertical rate” is blank
    - enter a value for the achieved rate (for aircraft flying level the value “0” must be entered), then click “Evaluate” button.
- “Achieved vertical rate” is non-numeric
    - enter a number for the achieved rate (do not include units), then click “Evaluate” button.

5.4. <u>Method B</u>

5.4.1. Method B evaluation is “NOT APPLICABLE” – possible causes and solutions:

- Compliance has not yet been evaluated
    - click the “Evaluate” button
- “Time of evaluation” is blank
    - enter a value for the time, then click “Evaluate” button.

- “Time of evaluation” is non-numeric
  - enter a number for the time (do not include units), then click “Evaluate” button.
- “Achieved vertical rate” is blank
  - enter a value for the achieved rate (for aircraft flying level the value “0” must be entered), then click “Evaluate” button.
- “Achieved vertical rate” is non-numeric
  - enter a number for the achieved rate (do not include units), then click “Evaluate” button.

5.4.2. Method B evaluation is “NOT KNOWN” – possible causes and solutions:

- “Time of evaluation” is not greater than standard pilot model response delay (*viz*. 5s for Initial RAs; 2.5s for Subsequent RAs)
  - enter a value greater than standard pilot model response delay, then click “Evaluate” button.

6. Abbreviations

ACAS	Airborne Collision Avoidance System
COC	Clear of Conflict
fpm	feet per minute
g	acceleration due to gravity
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IVSI	Instantaneous Vertical Speed Indicator
MVS	Maintain Vertical Speed
PFD	Primary Flight Display
RA	Resolution Advisory
SARPs	Standards and Recommended Practices
TCAS	Traffic alert and Collision Avoidance System
VBA	Visual Basic for Applications

7. References

1. *'Performance Assessment of Pilot Compliance with Traffic Collision Avoidance System Advisories Using Flight Data Monitoring, Guidance Material – 2nd Edition',* EUROCONTROL, IATA.

2. *'The Assessment of Pilot Compliance with TCAS RAs, TCAS Mode Selection and Serviceability Using ATC Radar Data'*, Ed. 2.1, EUROCONTROL, 9/4/2021.

3. *'Aeronautical Telecommunications, Annex 10, Volume IV – Surveillance and Collision Avoidance Systems'*, 5th Edition, ICAO, Jul 2014 (ISBN 978-92-9249-537-4).

4. '*Manual of the ICAO Standard Atmosphere'*, Doc. 7488/3, 3rd Edition, ICAO, 1993 (ISBN 92-9194-004-6),