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

Guidance Material – 2nd Edition

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1. Abbreviations and Acronyms

ACAS	Airborne Collision Avoidance System
ANSP	Air Navigation Service Provider
AP	Auto Pilot
ASR	Air Safety Report
ATC	Air Traffic Control
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
FMS	Flight Management Systems
FOQA	Flight Operational Quality Assurance
FSTD	Flight Simulation Training Devices
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
ICAO	International Civil Aviation Organization
IVSI	Instantaneous Vertical Speed Indicator
MOR	Mandatory Occurrence Report
MTE	Multi-threat encounter
OIPR	Opposite Initial Pilot Response
PNF	Pilot Not Flying
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
VSI	Vertical Speed Indicator

2. Objective

Similar to the first edition of the guidance material, this second edition has been prepared jointly by IATA and EUROCONTROL and is designed to support the understanding of the Traffic Alert and Collision Avoidance System II (TCAS II), and to provide updated information and guidance on technical and operational issues applicable to TCAS Resolution Advisory (RA) in order to facilitate operational monitoring. This guidance also provides brief information on the future ACAS X, short training animations, as well as an assessment of pilot compliance with RAs using radar data. However, this 2nd Edition is not, per se, designed for the complete training of pilots or any stakeholders.

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.

3. Introduction

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 and resolving threats. As the airspace continues to evolve, employment of updated versions of existing technologies or the development of new ones is needed.

There are currently two types of TCAS systems in operational use: 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 resolution advisory (RA). This alert directs the flight crew to make a vertical maneuver to avoid the intruding aircraft.

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

Three versions of TCAS II are approved and are currently in operation:

- Version 6.04a is still mandated or allowed on some aircraft operating in US airspace. In Europe version 6.04a may be found on aircraft outside the current European mandate (i.e. either military or those below the mandated weight or number of passenger seats thresholds). Version 6.04a is not compliant with the ICAO ACAS SARPS (Annex 10, volume IV). Assessment of pilot responses to RAs issued by version 6.04a are not covered in this Guidance Material.

- Version 7.0 is still mandated or allowed on many aircraft operating in US airspace and other parts of the world. In Europe version 7.0 may be encountered on aircraft outside the current European mandate (i.e. either military or those below the mandated weight or number of passenger seats thresholds). Version 7.0 was the first TCAS II version to be compliant with the ICAO ACAS SARPS (Annex 10 volume IV); however, since 2010 (amendment 85) only version 7.1 is compliant.

- Version 7.1 is the only ACAS version meeting the current requirements of ICAO and European mandates. It was developed based on an extensive analysis of version 7.0 performance, with two major safety modifications implemented to improve TCAS performance.

Operational monitoring of version 7.0 revealed the following two issues with pilots' responses to Reduce Climb/Descent RAs "Adjust vertical speed, adjust":

- Incorrect response: The aural annunciation associated with the Reduce Climb/Descent RAs, "Adjust vertical speed, adjust" did not clearly communicate what exact maneuver was required. That led to cases where pilots were increasing their vertical rate rather than reducing it, consequently causing a deterioration of the situation
- Level busts: When pilots following the Reduce Climb and Reduce Descent RAs flew through their cleared level, often causing a follow up RA for the other aircraft above or below and disrupting ATC operations.

These issues were solved in version 7.1 by replacing the "Adjust vertical speed, adjust" with a new "Level off, level off" RA.

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. ACAS 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 maneuvers. This system combines the AP/FD and the TCAS to provide vertical speed guidance based on a TCAS target and best avoidance maneuver in case of conflicting air traffic. It also avoids or reduces pilot overreaction, enhances safety and increases passenger comfort during the maneuver.

More recently, the ACAS X system, which is expected to become operational in the foreseeable future, is an improved system that is being funded by the United States Federal Aviation Administration (FAA). The ACAS X program is intended to bring enhancements to both surveillance and the advisory logic. This system will shift from the beacon-only surveillance of TCAS to a plug-and-play surveillance architecture that supports surveillance based on global positioning system (GPS) data. This improved system is intended not only to accommodate new procedures (such as those supporting 4D trajectory-based operations) but also to allow the use of other surveillance sources, as required to support new aircraft types such as remotely piloted aircraft. ACAS X is expected to improve on today's system without changing the cockpit interface, i.e. using the same alerts and presentation. (See page Appendix A "Future of Collision Avoidance: ACAS X" – An extract from the EUROCONTROL Operational Safety Study: TCAS RA not Followed).

For a deeper knowledge and understanding about TCAS performance, the Reader is advised to refer to the documentation listed in the Reference section of the Guide. This Guide has been designed to support the understanding of the TCAS systems and the training of people involved in the operations of TCAS. However, it is not, per se, designed for the complete training of controllers or pilots.

4. Pilot Responsibility

For the current TCAS II system to work as designed and to resolve a risk of midair collision, immediate and correct flight crew response to TCAS RA is required, unless it jeopardizes safety of the aircraft. This means that pilots will at times maneuver contrary to ATC instructions or disregard ATC instructions. 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.

In an event of an RA, any delayed or incorrect flight crew response negates the effectiveness of the RA, their actions will be the most important single factor affecting the performance of the TCAS system. Also, if the pilot 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 maneuver contrary to the RA as that could result in a collision with the threat aircraft. However, in case of a TCAS RA maneuver contrary to other critical cockpit warnings, pilots should respect those other critical warnings – responses to stall warning, wind shear, and 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;
- 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 maneuver correctly by flying the commanded vertical speed;
- Follow the RA even if there is a conflict between the RA and ATC instruction to maneuver;
- 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;
- Notify ATC when returning to the current clearance;
- The PNF (Pilot Not Flying) should provide updates on the traffic location and monitor the response to the RA. Proper crew resource management should be applied;
- Fill out an Air Safety Report form.

5. Performance Monitoring

In the event of an RA, the flight crew shall report upon flight completion the circumstances by means of Air Safety Report (ASR) / Mandatory Occurrence Report (MOR). The reporting of the RA by the flight crew is expected to open the parenthesis in the airline safety department in the identification of the contributing factors that will help assess and understand the root causes of the incidents.

A procedure should be in place for the controllers to secure radar data recordings for all reported TCAS events. These events are analyzed, and 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 radar data is found in Appendix B.

In addition to the pilot and controllers reports, a complimentary approach to the ASR 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 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 analyze 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 ASR/MOR filed by the flight crew?

The analyst should check if an ASR/MOR 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/MOR and it is expected that the pilots will do so. If the flight crew refuses, this is a regulatory non-compliance with to mandatory reporting. Airlines vary in how this scenario is dealt with, but typically a review group would be convened consisting of the safety manager, a pilot's representative and a flight operations manager. The group would decide whether the refusal to file an MOR constitutes sufficient reason to withdraw the flight crew's identity protection under the FOQA/FDM scheme.

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/MOR 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.

6. FOQA/FDM Review Group

The event will then be reviewed at the regular FOQA/FDM review meeting. This group may also recommend further mitigations such as a notice to all pilots regarding the company's procedure for responding to TCAS RAs and/or including TCAS RAs in the next round of simulator refresher training.

7. Regulations and Operational Guidance

Significant reductions in the occurrences of many of these issues 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 maneuver in response of an RA event.

8. 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 above-mentioned criteria. 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).

9. Conclusion

An operator must establish procedures on how their flight crews should operate TCAS and respond to RAs. Broadly speaking, operator's procedures should cover topics addressed in this document and, especially, ICAO provisions. These include, but are not limited to:

- Pilot responses to RAs;
- Pilot compliance with RAs;
- Aircraft operations during an RA;
- 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 still present. When an RA is generated correct action must be taken promptly. In addition to the recommendations listed in this document, initial/recurrent training as well as simulator training will enhance flight crew understanding of how the TCAS system works, how they should respond to RAs, as well as the limitations of TCAS. The pilot's response is a key component of the TCAS system.

In case of a TCAS RA event, the pilots shall report the circumstances by means of ASR / MOR. 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, analyzed 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.

10. Recommendations

TCAS has been deployed to act as a last safety net resort to mitigate the risk of midair collisions by providing flight crews 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 that the equipment is properly maintained;
- The pilots who operate TCAS-equipped aircraft have received the relevant training;
- Approved pilot training programs are implemented for initial and recurrent training;
- Procedures are in place for pilots to report a TCAS event and/or problems with TCAS performance;
- Procedures are in place to analyze any reported event and problem, and to provide feedback;
- 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, unless otherwise instructed by ATC;
- Pilots use prescribed phraseology to report RAs to ATC;
- Their pilots understand the potential risks of an improper response to an RA.

11. 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 and ACAS Xa is expected to become commercially available after 2020. At the time of writing, work is ongoing at ICAO to update the relevant Provisions to include ACAS Xa.

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 maneuvers 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 Air Traffic Control instructions or clearances.

During the encounter, the RA strength is evaluated every second. Occasionally, the threat aircraft maneuvers 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 maneuvers 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 maneuver contrary to the RA as that could result in a collision with the threat aircraft. However, in case a TCAS RA maneuver 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 0.25 g.

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

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 to 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; maneuver 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 VS tape, the pilot must make further pitch adjustments necessary to place the VS 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.

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 show sometimes imprecisions and fluctuations of vertical rates between updates. Therefore, while assessing pilot compliance a margin needs to be applied to rates listed below. RA responses were 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: 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 the green arc but more than the opposite sense(expect for the RAs when the 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).

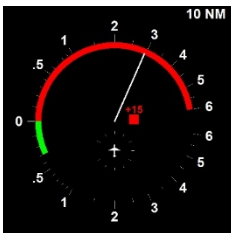
Given that the green arc is not displayed for preventive RAs (i.e. Monitor Speed RAs), the rules above cannot be applied to them. The evaluation of these RAs can only be done in the Followed and Opposite categories, as indicated by the red and black arcs.

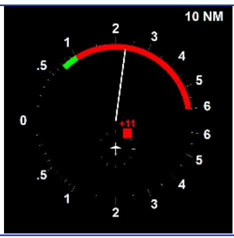
From a safety point of view the "Not Followed" and "Opposite" events are the most critical and call for particular attention and investigation.

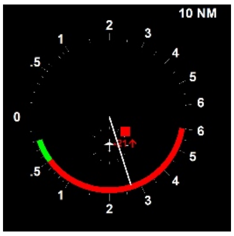
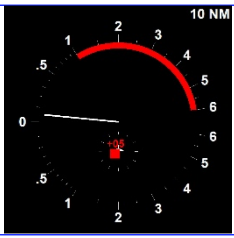
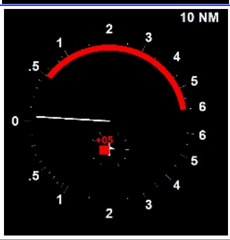
Table 1 below presents the assessment criteria, associated aural annunciation and IVSI examples for initial RAs for TCAS II versions 7.0 and 7.1 as well as ACAS Xa.

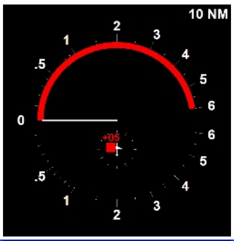
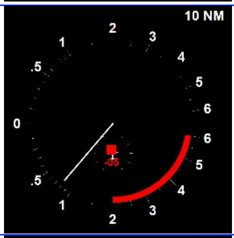
Table 1: Assessment criteria of pilot responses to initial RAs

Resolution Advisory *Aural annunciation*	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	**Pilot compliance assessment: Followed**	**Not 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
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%

Resolution Advisory / *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	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 [b) c)] *Level off, level off*		0 – 6000	-300 – 0	-500 – 300	301 – 500	> 500	< -500

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	Pilot compliance assessment: Followed	Not followed	Opposite	Excessive
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
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

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

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	Pilot compliance assessment			
				Followed	Not followed	Opposite	Excessive
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 only*
- *b) TCAS II version 7.1 only*
- *c) ACAS X only*

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).

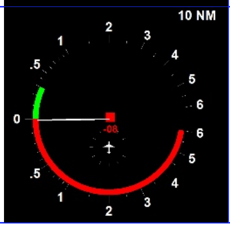
For Maintain Vertical Rate RAs, the Resolution Advisory Required Rate (RARR) value is used. As for these RAs, the required vertical rate RA will vary, depending on the aircraft's vertical rate at the time when the RA was issued. Therefore, the compliance can only be assessed if the required rate has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

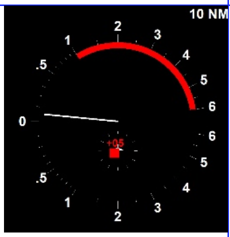
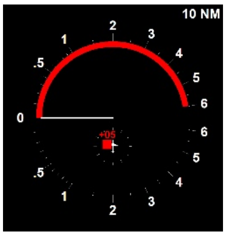
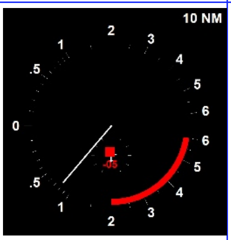
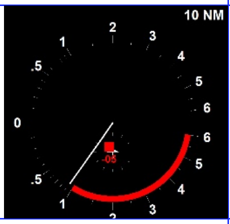
During an encounter, the RA may change. Table 2 below presents the assessment criteria, associated aural annunciation, IVSI examples for subsequent RAs for TCAS II versions 7.0 and 7.1 as well ACAS Xa.

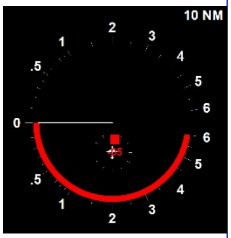
Table 2: Assessment criteria of pilot responses to subsequent RAs

Resolution Advisory	*Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	Pilot compliance assessment			
					Followed	Not 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
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

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	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
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	-3200 – -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%
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%

Resolution Advisory *Aural annunciation*	**IVSI Example**	**Prohibited vertical rates: red arc range**	**Required vertical rates: green arc range**	**Pilot compliance assessment**			
				Followed	**Not followed**	**Opposite**	**Excessive**
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
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

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	Pilot compliance assessment			
				Followed	Not followed	Opposite	Excessive
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
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

Resolution Advisory *Aural annunciation*	IVSI Example	Prohibited vertical rates: red arc range	Required vertical rates: green arc range	Pilot compliance assessment			
				Followed	Not followed	Opposite	Excessive
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 only*
- **b)** *TCAS II version 7.1 only*
- **c)** *ACAS X only*

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 maneuver was too weak, excessive or opposite to the issued RA should also be analyzed 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 maneuvers, 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 Airbus 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 maneuver (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 maneuvers 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 radar 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 radar data and Mode S downlink messages. Radar data will allow simulating (recreating) RAs (using specialized software tools); however, this technique may not always be accurate (due to inaccuracy of radar data, infrequent updates and data distortion by radar 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 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 maneuver 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.

12. 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 analyze 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.

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.

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

It should be considered how the FDM data is used and analyzed by the aircraft operator in order to mitigate hazards and apply adequate measures for safety improvement.

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 analysis included a total of 5,539 events that corresponded to TCAS RA triggered on board since 2016.

Figure 1 illustrates the occurrence per region of the participating airlines in FDX program

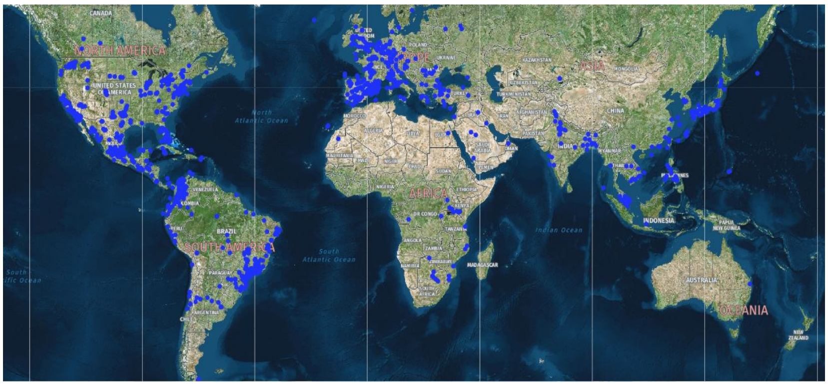


Figure 1: The occurrence per region of the participating airlines in FDX

Figure 2 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 0.209 per 1000 flights.

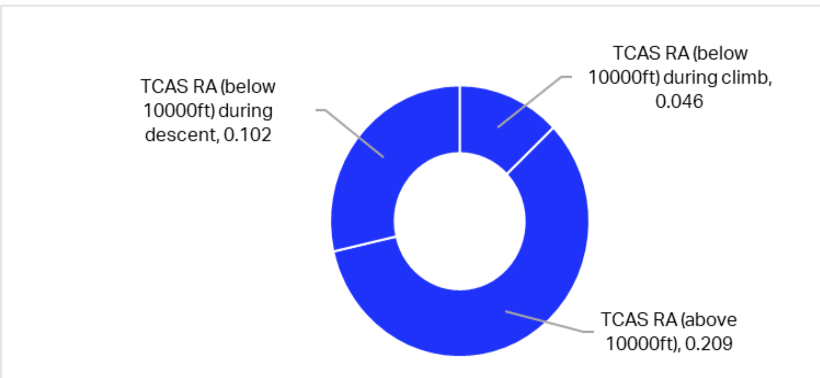


Figure 2: TCAS RA Occurrence by Altitude band

Figure 3 illustrates the TCAS RA per altitude band by region of participating airlines in the FDX program

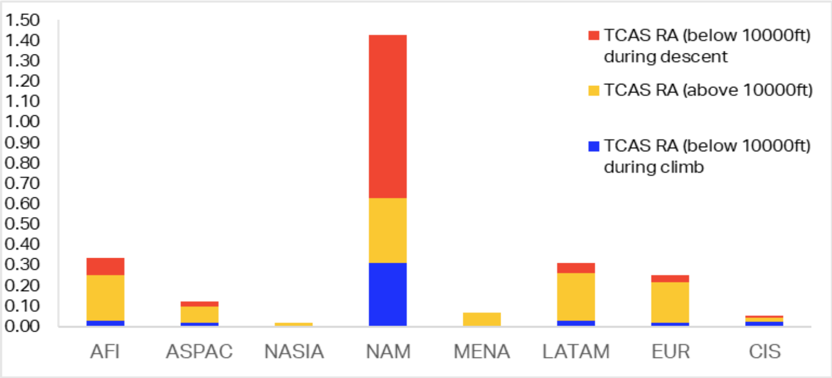


Figure 3: TCAS RA per Altitude Band by Region of Participating Airlines

Figure 4 depicts the distribution of TCAS RA event by aircraft propulsion per year for airlines participating in FDX program.

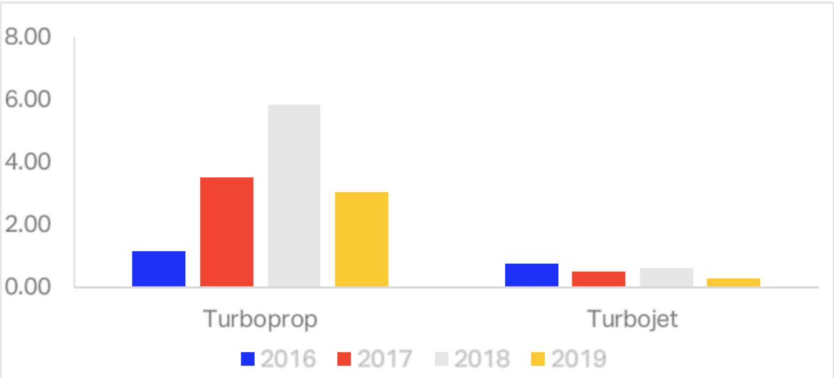


Figure 4: TCAS RAs by Aircraft Propulsion per Year

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 two examples of animations here on TCAS RA. The first one is extracted from FDX Global Animation Archive and the second one is provided courtesy of SKYbrary. To view the animation in Figure 5, please click on the red pin.

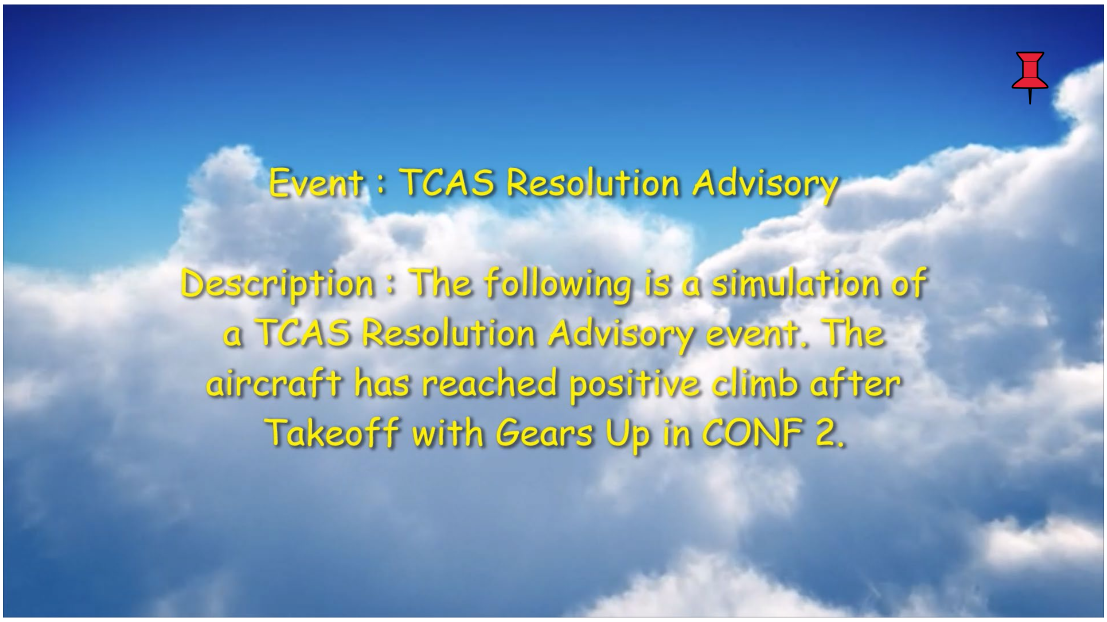


Figure 5: Animation _ TCAS RA Source IATA GADM

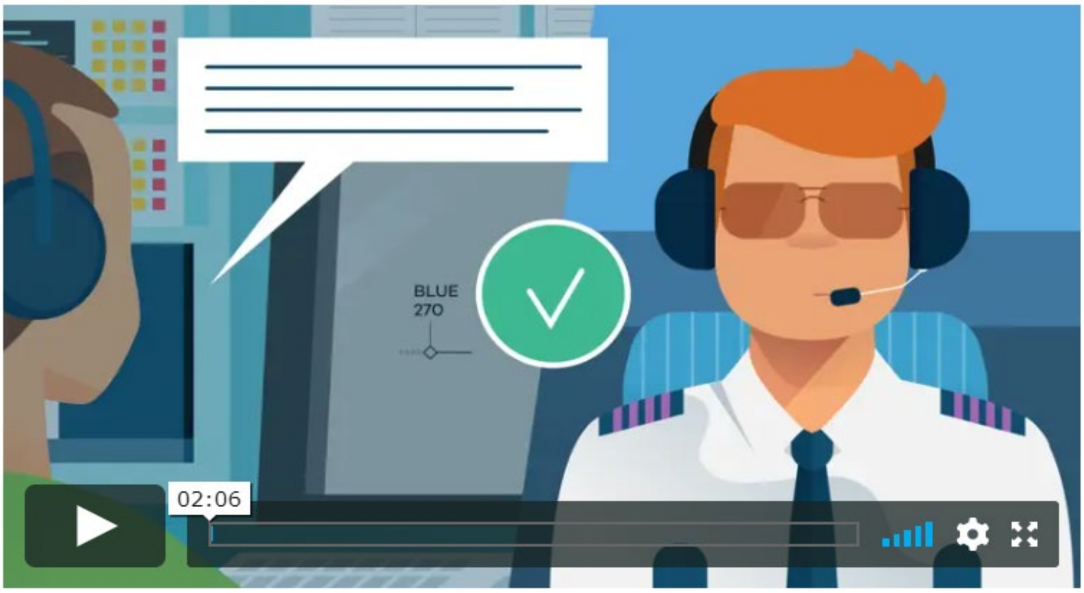


Figure 6: Animation _ TCAS RA Source SKYbrary

TCAS Monitoring

TCAS monitoring programs should periodically publish findings from their analysis of TCAS events. The results of these analysis 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.

References

- Guidance Material: Performance assessment of pilot compliance to Traffic Alert and Collision Avoidance System (TCAS) using Flight Data Monitoring (FDM), IATA and EUROCONTROL, Edition 1, January 2019.
- ACAS Guide - Airborne Collision Avoidance, EUROCONTROL
- EUROCONTROL Operational Safety Study: TCAS RA not Followed
- 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 (Second edition – 2012, amendment 1 – 2017).
- EUROCONTROL ACAS Guide – Airborne Collision Avoidance. December 2017.
- 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 detailed statistical data as well as the description of the methodology is available on SKYbrary, to view please click here.

The information presented below is based on version 1.0 of the report. Any subsequent updates and revisions will be available under the same SKYbrary link.

1 Data set

EUROCONTROL used radar data, which was gathered recently in core European airspace over a period of 12 months, to assess pilot compliance with TCAS RAs.

When a Resolution Advisory (RA) is generated the aircraft's transponder can downlink a message providing details of RAs and RA termination to a Mode S ground station on each radar interrogation. Each downlinked RA message also contains details concerning the threat aircraft. These RA downlink messages were used for this study. The data collected comprises over nine million flight hours and more than one million encounters, i.e. cases when two aircraft were in proximity, but not necessarily close enough to trigger an RA.

Based on the Mode S RA downlink data, the subset of aircraft in the one million encounter set which experienced an RA was determined (see Table 1): altogether 1373 RAs were recorded in 1022 encounters. In the majority of encounters (84%), only one aircraft in the conflict pair experienced an RA. Out of all RA downlinks, not a single multi-threat encounter was recorded in the dataset; consequently, they are not part of the assessment.

Table 1. The final number of encounters and RAs taken into the assessment.

Total encounters with at least one aircraft having single RA	1022
The total number of all RAs	1373
Coordinated encounters (i.e. both aircraft get an RA)	162
Uncoordinated encounters	860
Equipped – Mode S	821
Equipped – Mode A/C encounters	29

The Mode S downlink data was analysed and any RA downlink messages that were of short duration (i.e. the RA was recorded during only one update cycle), corrupt or inconsistent were filtered out. Further analysis of the 1184 RAs of over 8 seconds duration was carried out. Some of these RAs, as shown in Table 2 below, lasted for 12 seconds or longer (1008) or 16 seconds or longer (823).

In 171 cases the first RA changed (i.e. either strengthened, reversed or weakened) and in a further 18 cases there was at least one further RA change (see Table 2 below).

Table 2. The number of all RAs evaluated in the assessment, classified by minimum duration and the moment of being displayed.

1st RAs analysed – a total duration of each RA lasted for 8 seconds or longer	1184
1st RAs analysed – a total duration of each RA lasted for 12 seconds or longer	1008
1st RAs analysed – a total duration of each RA lasted for 16 seconds or longer	823
2nd RAs analysed – a total duration of each RA lasted for 8 seconds or longer	171
2nd RAs analysed – a total duration of each RA lasted for 12 seconds or longer	130
2nd RAs analysed – a total duration of each RA lasted for 16 seconds or longer	100
3rd and more RAs analysed – a total duration of each RA lasted for 8 seconds or longer	18
3rd and more RAs analysed – a total duration of each RA lasted for 12 seconds or longer	14
3rd and more RAs analysed – a total duration of each RA lasted for 16 seconds or longer	8

As per IATA/EUROCONTROL's Guidance Material, RAs shorter than 8 seconds were not taken into account (as they may not give the pilot an opportunity to respond and change aircraft's vertical rate as required).

Nominally, a response to an initial RA is expected within 5 seconds with aircraft acceleration of 0.25g (see ICAO ACAS Manual (Doc. 9863)). Using ICAO's standard pilot model, it has been calculated that the pilots may not be able to achieve the RA required vertical rate within the 8-second period. For example, in artificially created case of a Descend RA the required rate of -1500 ft/min. was not achieved after 8 seconds (see Figure 1). Consequently, the analysis of pilot responses was extended to include the assessment at 12 and 16 seconds after the RA to establish whether the pilots manage to achieve the required vertical rates within the corresponding period.

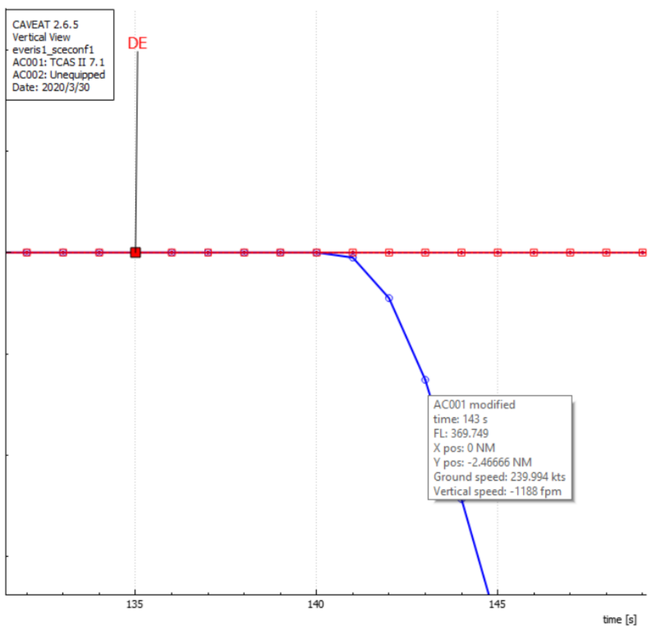


Figure 1: Simulation results 8 seconds after an RA was generated.

2 Limitations and assumptions

The following limitations and assumptions of this study should be noted:

- Radar recordings are subject to a latency of up to 4 seconds (due to radar antenna rotation); therefore, events such as RAs or RA termination occur in the preceding 4-second period but the timing cannot be precisely determined (RA messages are downlinked without a timestamp);
- Altitudes and vertical rates may be inaccurately determined by the ATC system tracker. In order to deliver optimal display performance of radar data to air traffic controllers, the ATC system tracker software makes assumptions regarding the estimated position of tracks and approximates the data accordingly. The “tracker effect” has been significantly reduced by applying additional filtration;
- All aircraft were assumed to be equipped with TCAS II version 7.1;
- Pilot compliance criteria are based on IATA/EUROCONTROL Guidance Material;
- As Mode S RA downlink messages do not provide the RA Required Rate (RARR) for Maintain Vertical Speed RAs, the RARR value was assumed to be equivalent to the aircraft’s vertical rate as recorded at the time when the RA downlink message was received;
- Mode S RA downlink messages do not provide the corresponding vertical speed limits for Monitor Vertical Speed RAs – consequently it was not possible to assess these RAs. Nevertheless, Monitor Vertical Speed RAs are included in the global RA statistics.

3 Results

Based on the IATA/EUROCONTROL Guidance Material, pilot responses have been classified into following categories:

- **Followed:** the pilot's reaction is correct and the anticipated vertical speed is achieved,
- **Not followed - too weak** response, the vertical rate was not sufficient to fulfil IATA guidance requirements, (subsequently, referred to as "not followed" for brevity).
- **Opposite**: the action performed by pilot is in the opposite vertical sense comparing to the instruction generated by TCAS,
- **Excessive**: the response exceeds the required vertical rate

Comprehensive information about all RAs, aural annunciations and required vertical rates is contained in the IATA/EUROCONTROL Guidance Material.

3.1 Pilot compliance with RAs – duration of 8 seconds or longer

As shown in below in Table 3 below in the set of 1184 RAs, the majority of RAs (64%) were Level Off RAs. These RAs are typically issued when an aircraft is approaching its cleared level with a high vertical rate and an RA is generated against an aircraft at the adjacent level. The highest number of "not followed" RAs after 8 seconds was recorded for Climb and Crossing Climb RAs. While the Level Off RAs were best complied with (compared to other RAs), nearly half of Level Off RAs (in whichever vertical sense) were flown in the opposite direction. Opposite reactions are the most critical cases from the safety point of view.

Overall pilot compliance after 8 seconds of initial RAs is shown in Figure 2 below.

Table 3. All types of first RAs - 8 seconds or longer.

First RA - 8-second duration or longer					
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)	The total number of each RA type (100%=1184)
Climb	34 (22.52)	86 (56.95)	27 (17.88)	4 (2.65)	151 (12.75)
Descend/Crossing Descend	31 (25.41)	79 (64.75)	7 (5.74)	5 (4.10)	122 (10.30)
Level Off – Upwards	148 (41.81)	41 (11.58)	143 (40.40)	22 (6.21)	354 (29.90)
Level Off – Downwards	178 (43.73)	42 (10.32)	172 (42.26)	15 (3.69)	407 (34.38)
Maintain Vertical Speed	3 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	3 (0.25)
Monitor Vertical Speed	Not assessed				147 (12.42)
Total (100%=1184-Monitor Vertical Speed)	394 (37.99)	248 (23.92)	349 (33.65)	46 (4.44)	

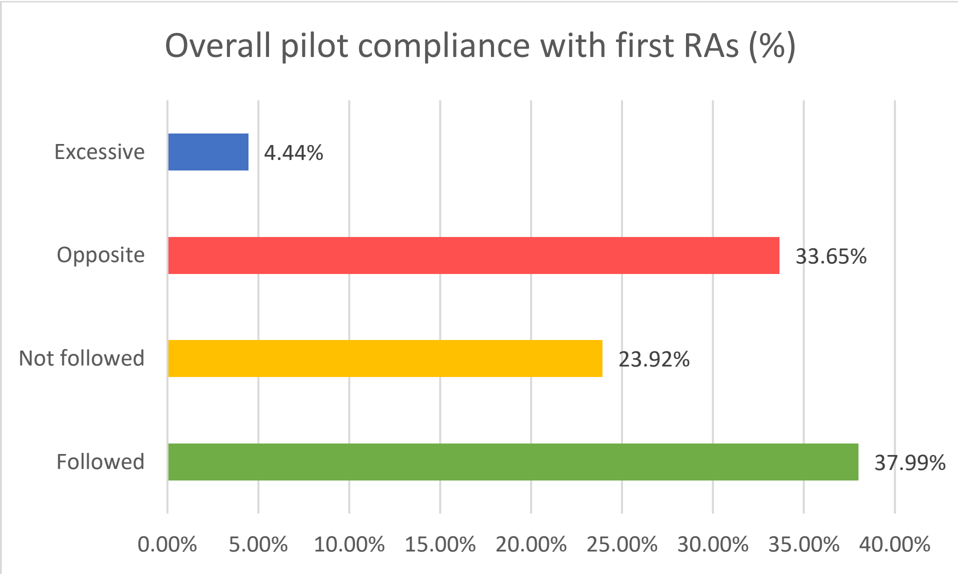


Figure 2. Pilot compliance with first RAs (%) - 8 seconds or longer.

In the following sections, pilot responses to each type of RA after 8 seconds, per altitude band, as well RA durations will be examined.

3.1.1 Climb RAs – duration of 8 seconds or longer

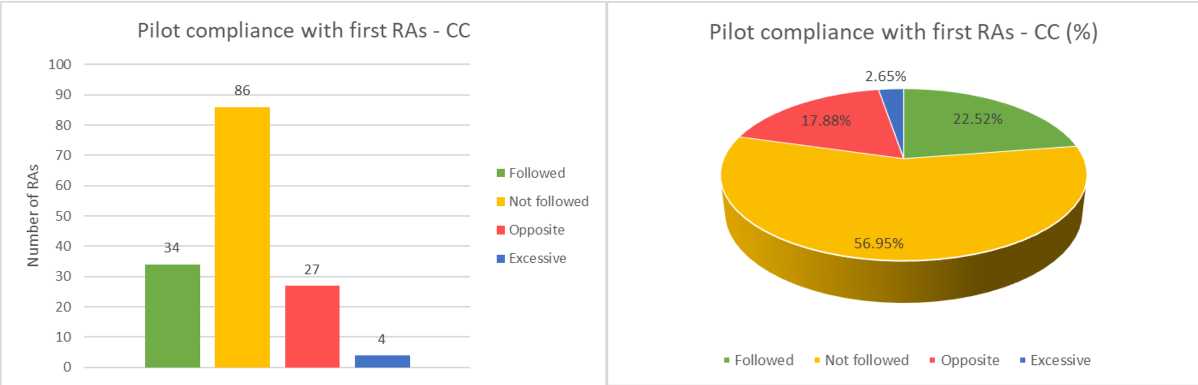


Figure 3.Pilot Compliance with first Climb RAs – 8 seconds or longer.

Table 4. Climb RAs – 8-second duration or longer, altitude bands.

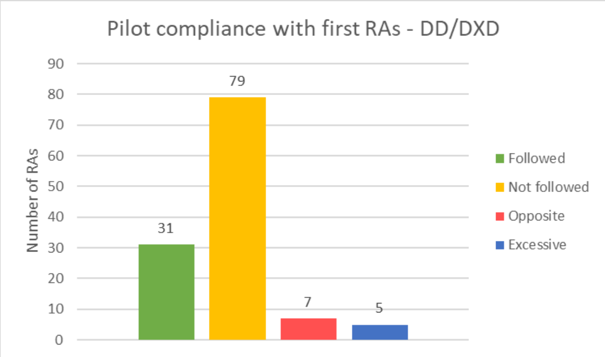
Pilot compliance based on altitude – 151 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	3 (1.99)	2 (1.32)	6 (3.97)	0 (0.00)
FL30 - FL100	8 (5.30)	29 (19.21)	13 (8.61)	1 (0.66)
FL100 - FL180	9 (5.96)	13 (8.61)	2 (1.32)	0 (0.00)
FL180 - FL290	9 (5.96)	22 (14.57)	4 (2.65)	1 (0.66)
Above FL290	5 (3.31)	20 (13.25)	2 (1.32)	2 (1.32)

Table 5. Climb RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	84
Average [s]	13.17

Very few Climb RAs were followed correctly (between 2% and 6%) regardless of the altitude band (see Table 4). As many as 19% of Climb RAs were not followed in the FL30 – FL100. Typically, it is believed that pilots tend not to follow RAs at lower altitudes due to visual acquisition, which is more likely than at the higher altitudes as a result of lower closing speeds and reduced separation. However, the data here indicates that the RAs were also not followed or even flown in the opposite direction at higher altitudes, contradicting this belief.

3.1.2 Descend/Crossing Descend RAs – duration of 8 seconds or longer



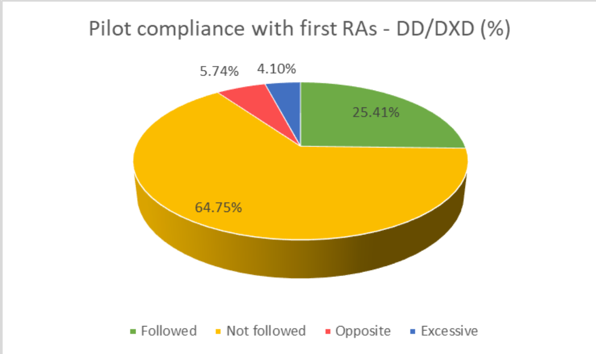


Figure 4. Pilot Compliance with first Descend/Crossing Descend RAs – 8 seconds or longer

Table 6. Descend/Crossing Descend RAs –8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 122 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	2 (1.64)	6 (4.92)	1 (0.82)	0 (0.00)
FL30 - FL100	16 (13.11)	15 (12.30)	5 (4.10)	1 (0.82)
FL100 - FL180	0 (0.00)	5 (4.10)	1 (0.82)	0 (0.00)
FL180 - FL290	6 (4.92)	23 (18.85)	0 (0.00)	1 (0.82)
Above FL290	7 (5.74)	30 (24.59)	0 (0.00)	3 (2.46)

Table 7. Descend/Crossing Descend RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	100
Average [s]	15.90

Similarly to Climb RAs, very few Descend and Crossing Descend RAs were followed correctly (between 2% and 13%) regardless of the altitude band (see Table 6). Almost a quarter of Descend RAs were not followed in the highest altitude band. There were very few opposite reactions to Descend RAs.

3.1.3 Level off RAs upwards sense – duration of 8 seconds or longer.

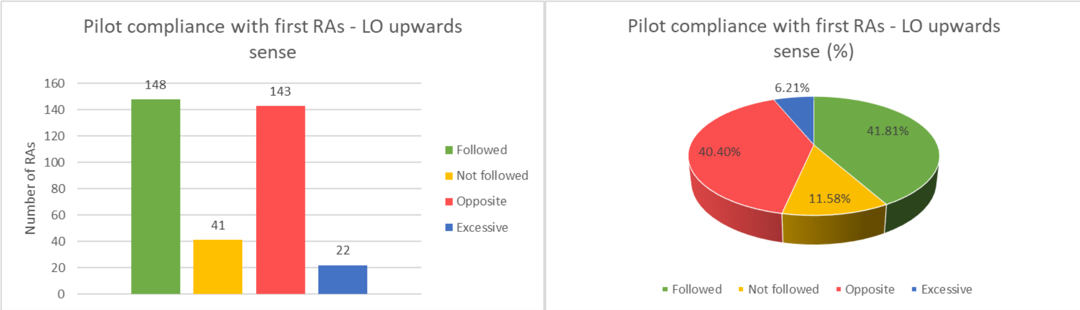


Figure 5. Pilot compliance with first RAs – Level off upwards sense – 8 seconds or longer.

Table 8. Level off RAs upwards sense – 8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 354 registered RAs represents 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	2 (0.56)	0 (0.00)	3 (0.85)	1 (0.28)
FL30 - FL100	20 (5.65)	4 (1.13)	18 (5.08)	3 (0.85)
FL100 - FL180	24 (6.78)	9 (2.54)	11 (3.11)	3 (0.85)
FL180 - FL290	42 (11.86)	9 (2.54)	53 (14.97)	9 (2.54)
Above FL290	60 (16.95)	19 (5.37)	58 (16.38)	6 (1.69)

Table 9. Level Off upwards sense RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	204
Average [s]	28.73

3.1.4 Level off RAs downwards sense – duration of 8 seconds or longer

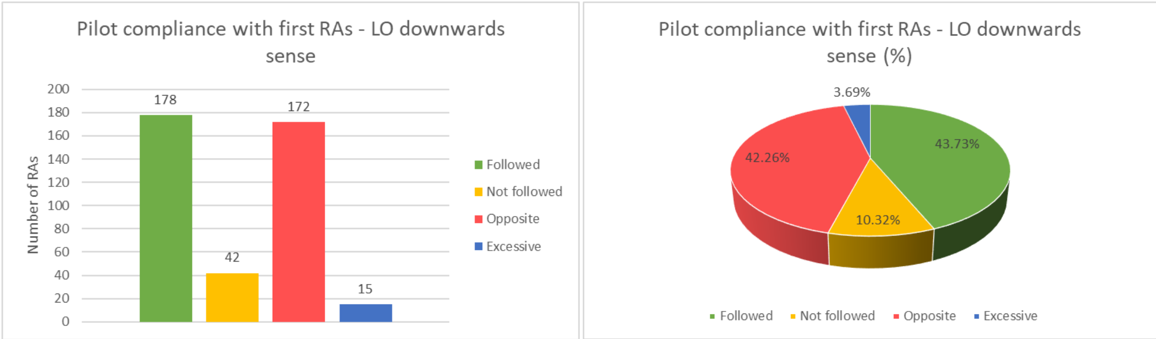


Figure 6. Pilot Compliance with first Level Off downwards sense RAs – 8 seconds or longer.

Table 10. Level Off RAs downwards sense – 8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 407 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	0 (0.00)	1 (0.25)	0 (0.00)	0 (0.00)
FL30 - FL100	22 (5.41)	5 (1.23)	37 (9.09)	1 (0.25)
FL100 - FL180	15 (3.69)	2 (0.49)	24 (5.90)	2 (0.49)
FL180 - FL290	40 (9.83)	17 (4.18)	44 (10.81)	6 (1.47)
Above FL290	101 (24.82)	17 (4.18)	67 (16.46)	6 (1.47)

Table 11. Level Off downwards sense RAs Duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	316
Average [s]	27.80

3.1.5 Maintain Vertical Speed – duration of 8 seconds or longer

Only 3 Maintain Vertical Speed RAs were observed in the dataset. All 3 occurred below 18000ft and were followed. However, this number is too low to assess pilot compliance with any statistical confidence.

3.2 Secondary RAs – duration of 8 seconds or longer

During the course of the encounter, the RA strength is evaluated every second. Occasionally, the threat aircraft will manoeuvre vertically in a manner that thwarts the effectiveness of the issued RA. In these cases, the initial RA will be modified to either increase the strength or reverse the sense of the initial RA. On the other hand, if the collision avoidance logic determines that the response to the initial RA has provided the sufficient vertical distance, the initial RA will be weakened to limit any unnecessary altitude deviation.

In case of strengthening or reversal RAs, prompt and correct pilot responses are particularly important, as these RAs indicate the initially chosen collision avoidance manoeuvre was not effective and a change is needed to prevent a collision.

In this study, a secondary RA was issued in 171 cases (see Table 12), most of them (over 81%) were weakening RAs. Over half of strengthening and reversal RAs were not followed or were flown in the opposite direction, which is particularly concerning. Excessive reaction to weakening RAs (Level Offs) is potentially explained by the hesitation of pilots to reduce the vertical rate of the initial RA (to ensure, from the pilot perspective, sufficient vertical spacing). Globally, the compliance with the secondary RA is much better that with the first RA (48% vs 38%).

Table 12. All types of secondary RAs –8 seconds or longer.

Secondary RA – 8-second duration or longer					
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)	The total number of each RA type (100% = 171)
Climb	3 (27.27)	6 (54.55)	2 (18.18)	0 (0.00)	11 (6.43)
Reversal Climb	0 (00.00)	1 (50.00)	1 (50.00)	0 (00.00)	2 (1.17)
Increase Climb	1 (100.00)	0 (0.00)	0 (00.00)	0 (0.00)	1 (0.58)
Descend/Crossing Descend	3 (25.00)	6 (50.00)	2 (16.67)	1 (8.33)	12 (7.02)
Reversal Descend	2 (66.67)	0 (00)	0 (00.00)	1 (33.33)	3 (1.75)
Level Off – Upwards	43 (51.19)	1 (1.19)	3 (3.57)	37 (44.05)	84 (49.12)
Level Off – Downwards	28 (50.00)	0 (0.00)	0 (0.00)	27 (49.09)	55 (32.16)
Maintain Vertical Speed	2 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	2 (1.17)
Monitor Vertical Speed	Not assessed				1 (0.58)
Total (100% =171-Monitor Vertical Speed)	82 (48.24)	14 (8.24)	8 (4.71)	66 (38.82)	

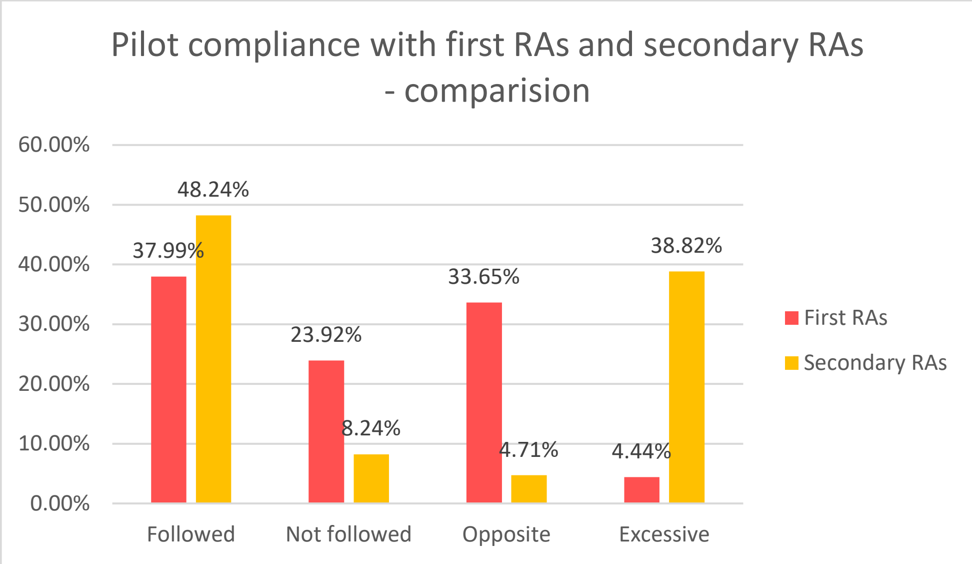


Figure 7. Pilot compliance with initial and secondary RAs – 8 seconds or longer.

3.3 Third and subsequent RAs – duration of 8 seconds or longer

Only 18 RAs subsequent to a secondary RA were recorded in the dataset (see Table 13). The number is not sufficient to conduct any analysis on this subset of data.

Table 13. All types of third and subsequent RAs – 8 seconds or longer.

Third and subsequent RAs – 8-second duration or longer					
Type	Followed	Not followed - too weak	Opposite	Excessive	Total
Climb/Reversal Climb	1	3	0	0	4
Descend/Crossing Descend/Reversal Descend	0	1	0	0	1
Level Off – Upwards	3	0	0	2	5
Level Off – Downwards	2	0	0	5	7
Monitor Vertical Speed	1	0	0	0	1
Total	7	4	0	7	18

3.4 Pilot compliance with RAs – duration of 12 seconds or longer

Out of 1184 first RAs, 1008 (85%) lasted 12 seconds or longer. In this data subset the number of RAs followed has increased (from 38% to 55%) and the number of RAs not followed decreased (from 24% to 16%). The improvement is most likely associated with the extension of the assessment time frame from 8 to 12 seconds, consequently giving the pilots more time to respond and achieve the required vertical rate.

Table 14. All types of first RAs – 12 seconds or longer.

First RA - 12-second duration or longer					
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)	The total number of each RA type (100%=1008)
Climb	20 (21.28)	51 (54.26)	16 (17.02)	7 (7.45)	94 (9.33)
Descend/Crossing Descend	27 (30.68)	53 (60.23)	5 (5.68)	3 (3.41)	88 (8.73)
Level Off – Upwards	217 (67.60)	22 (6.85)	49 (15.26)	33 (10.28)	321 (31.85)
Level Off – Downwards	220 (59.14)	18 (4.84)	83 (22.31)	51 (13.71)	372 (36.90)
Maintain Vertical Speed	1 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.10)
Monitor Vertical Speed	Not assessed				147 (12.42)
Total (100%=1008-Monitor Vertical Speed)	485 (55.37)	144 (16.44)	153 (17.47)	94 (10.73)	

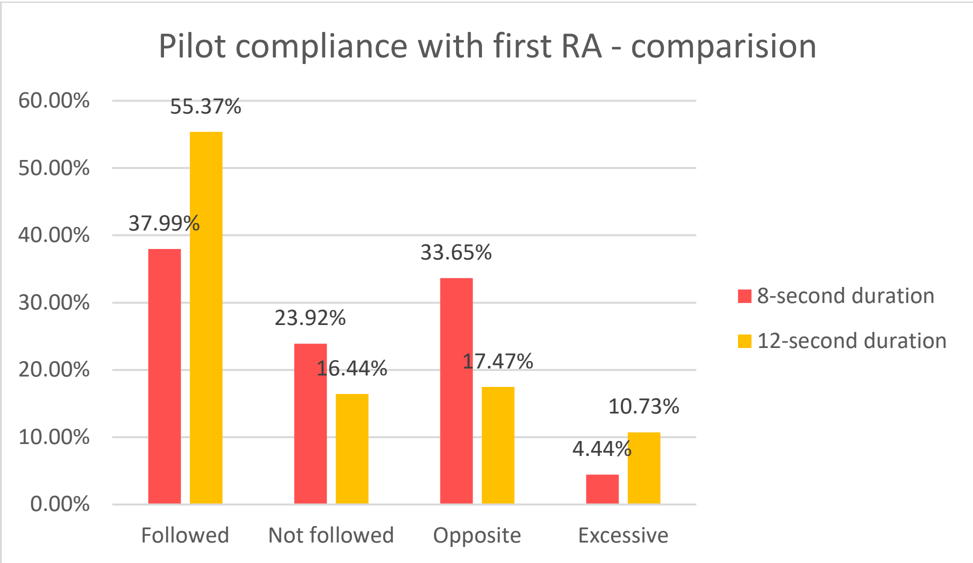
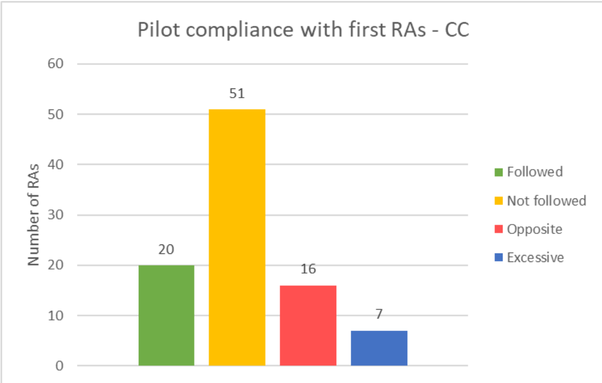


Figure 8. Pilot compliance with first RAs – comparison of the results.

The results for each RA type that lasted 12 seconds or longer are presented below.

3.4.1 Climb RA – duration of 12 seconds or longer



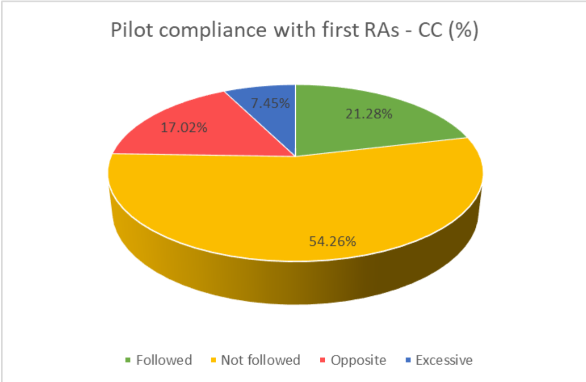


Figure 9. Pilot Compliance with first Climb RAs – 12 seconds or longer.

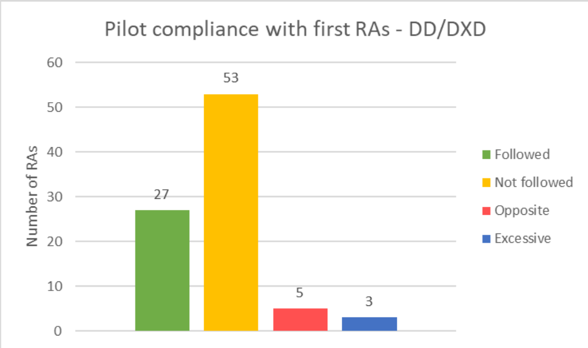
Table 15. Climb RAs – 12- second duration or longer, altitude bands.

Pilot compliance based on altitude – 94 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	1 (1.06)	3 (3.19)	4 (4.26)	0 (0.00)
FL30 - FL100	4 (4.26)	20 (21.28)	9 (9.57)	1 (1.06)
FL100 - FL180	5 (5.32)	4 (4.26)	2 (2.13)	1 (1.06)
FL180 - FL290	4 (4.26)	14 (14.89)	0 (0.00)	3 (3.19)
Above FL290	6 (6.38)	10 (10.64)	1 (1.06)	2 (2.13)

Table 16. CC RAs duration, 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	84
Average [s]	16.30

3.4.2 Descend/Crossing Descend RA – duration of 12 seconds or longer



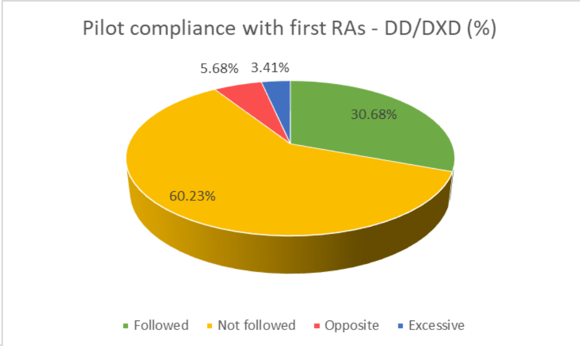


Figure 10. Pilot Compliance with first RAs – Descend/Crossing Descend – 12 seconds or longer.

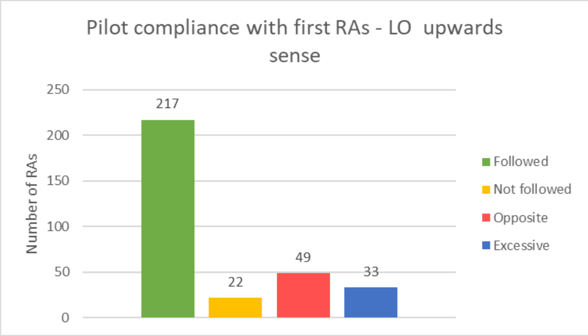
Table 17. Descend/Crossing Descend RAs – 12-second duration or longer, altitude bands.

Pilot compliance based on altitude – 88 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	1 (1.14)	6 (6.82)	0 (0.00)	0 (0.00)
FL30 - FL100	9 (10.23)	15 (17.05)	3 (3.41)	0 (0.00)
FL100 - FL180	2 (2.27)	3 (3.41)	1 (1.14)	0 (0.00)
FL180 - FL290	7 (7.95)	14 (15.91)	1 (1.14)	0 (0.00)
Above FL290	8 (9.09)	15 (17.05)	0 (0.00)	3 (3.41)

Table 18.Descend/Crossing Descend RAs duration, 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	84
Average [s]	16.30

3.4.3 Level off RAs upwards sense – duration of 12 seconds or longer



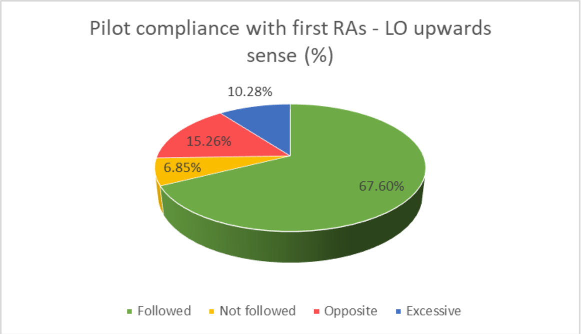


Figure 11. Pilot Compliance with first RAs – LO upwards sense– 12 seconds or longer.

Table 19. Level Off upwards sense – 12-second duration or longer, altitude bands.

Pilot compliance based on altitude – 321 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	2 (0.62)	1 (0.31)	1 (0.31)	1 (0.31)
FL30 - FL100	23 (7.17)	2 (0.62)	8 (2.49)	2 (0.62)
FL100 - FL180	36 (11.21)	1 (0.31)	4 (1.25)	3 (0.93)
FL180 - FL290	63 (19.63)	9 (2.80)	17 (5.30)	13 (4.05)
Above FL290	93 (28.97)	9 (2.80)	19 (5.92)	14 (4.36)

Table 20. Level Off upwards sense RAs duration, 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	204
Average [s]	30.87

3.4.4 Level off RAs downwards sense – duration of 12 seconds or longer

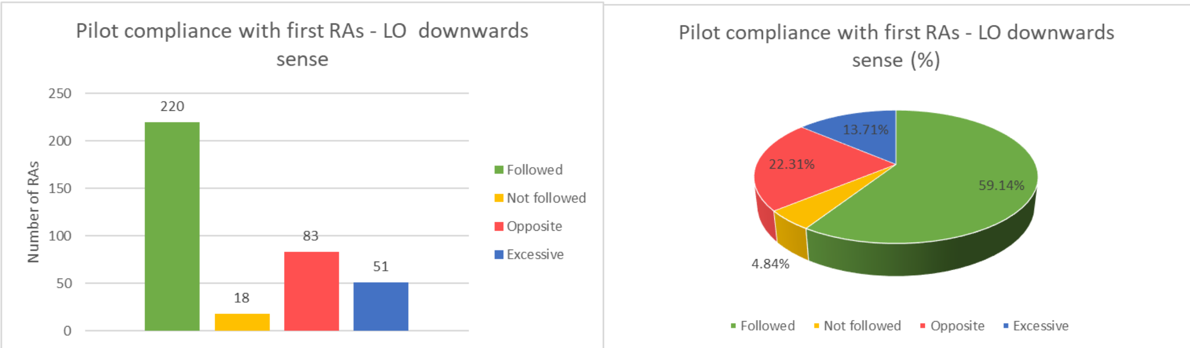


Figure 12.Pilot Compliance with first Level Off downwards sense RAs –12 seconds or longer.

Table 21. Level Off downward sense RAs – 12-second duration or longer, altitude bands.

Pilot compliance based on altitude – 372 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	0 (0.00)	0 (0.00)	1 (0.27)	0 (0.00)
FL30 - FL100	31 (8.33)	5 (1.34)	18 (4.84)	2 (0.54)
FL100 - FL180	18 (4.84)	3 (0.81)	13 (3.49)	4 (1.08)
FL180 - FL290	67 (18.01)	5 (1.34)	16 (4.30)	12 (3.23)
Above FL290	104 (27.96)	5 (1.34)	35 (9.41)	33 (8.87)

Table 22. Level Off downwards sense RAs Duration, 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	316
Average [s]	29.44

3.4.5 Maintain Vertical Speed – duration of 12 seconds or longer

Only one Maintain Vertical Speed RAs were observed in the dataset. It occurred between FL30 and FL100 and was followed. Again, the number of Maintain Vertical Speed RAs taken into the assessment is too low to make any significant conclusions.

3.5 Secondary RA – duration of 12 seconds or longer

Out of 171 recorded secondary RAs, 130 (76%) lasted 12 seconds or longer. Here, the Level Off RAs have the highest level of compliance. There are some cases of RAs not followed, opposite reactions or excessive response, but these numbers are too small to draw any conclusions based on them.

Table 23. All types of secondary RAs – 12 seconds or longer

Secondary RA – 12-second duration or longer					
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)	The total number of each RA type (100%=130)
Climb	0 (0.00)	4 (80.00)	1 (20.00)	0 (0.00)	5 (3.85)
Reversal Climb	0 (00.00)	1 (100.00)	0 (00.00)	0 (00.00)	1 (0.77)
Increase Climb	1 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.77)
Descend/Crossing Descend	3 (33.33)	5 (56.56)	1 (11.11)	0 (0.00)	9 (6.92)
Reversal Descend	1 (100.00)	0 (00.00)	0 (00.00)	0 (00.00)	1 (0.77)
Level Off – Upwards	48 (75.00)	2 (3.13)	3 (4.69)	11 (17.19)	64 (49.23)
Level Off – Downwards	32 (68.09)	1 (2.13)	1 (2.13)	13 (27.66)	47 (36.15)
Maintain Vertical Speed	1 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.77)
Monitor Vertical Speed	Not assessed				1 (0.77)
Total (100% =130-Monitor Vertical Speed)	86 (66.67)	13 (10.08)	6 (4.65)	24 (18.60)	

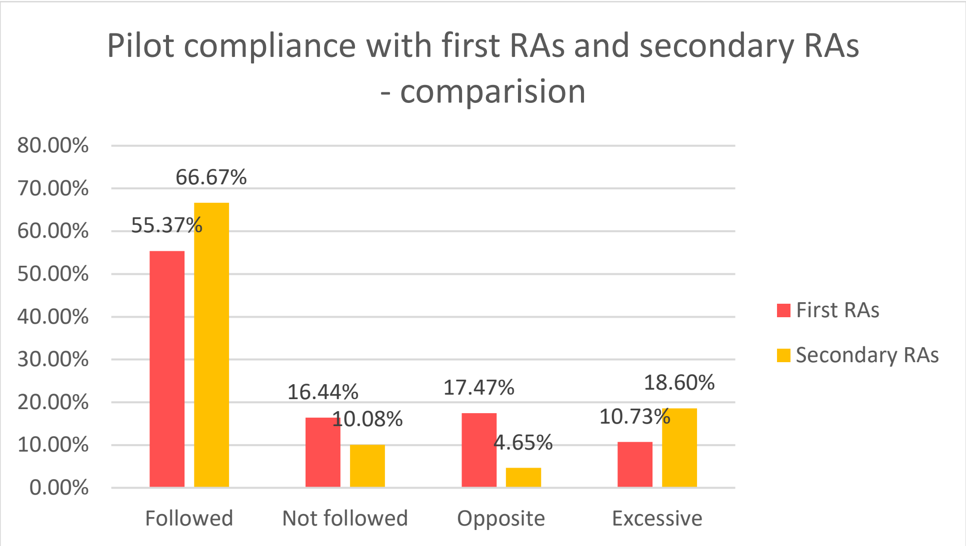


Figure 13. Pilot compliance with initial and secondary RAs – 12 seconds or longer.

3.6 Third RA and subsequent RAs – duration of 12 seconds or longer

Table 24. All types of third and subsequent RAs – 12 seconds or longer.

Third and subsequent RAs – a 12-second duration or longer					
Type	Followed	Not followed – too weak	Opposite	Excessive	Total
Climb/Reversal Climb	1	3	0	0	4
Descend/Crossing Descend/Reversal Descend	0	1	0	0	1
Level Off – Upwards	2	0	0	1	3
Level Off – Downwards	2	0	0	4	6
Total	5	4	0	5	14

Due to insufficient number of RAs, pilot compliance assessment cannot be performed for the tertiary and subsequent RAs.

3.7 Pilot compliance – duration of 16 seconds or longer

Out of 1184 recorded RAs, 823 (70%) lasted 16 seconds or longer. It is concerning that in several cases, for both Climb and Descend RAs, pilots did not achieve the required rate even after 16 seconds.

Table 25. All types of first RAs – 16 seconds or longer.

First RA - 16-second duration or longer					
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)	The total number of each RA type (100%=823)
Climb	6 (13.64)	20 (45.45)	10 (22.73)	8 (18.18)	44 (5.35)
Descend/Crossing Descend	9 (20.93)	28 (65.12)	3 (6.98)	3 (6.98)	43 (5.22)
Level Off – Upwards	198 (70.21)	12 (4.26)	21 (7.45)	51 (18.09)	282 (34.26)
Level Off – Downwards	200 (58.31)	19 (5.54)	47 (13.70)	77 (22.45)	343 (41.68)
Maintain Vertical Speed	1 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	1 (0.12)
Monitor Vertical Speed	Not assessed				110 (13.36)
Total (100%=823-Monitor Vertical Speed)	414 (58.06)	79 (11.08)	81 (11.36)	139 (19.50)	

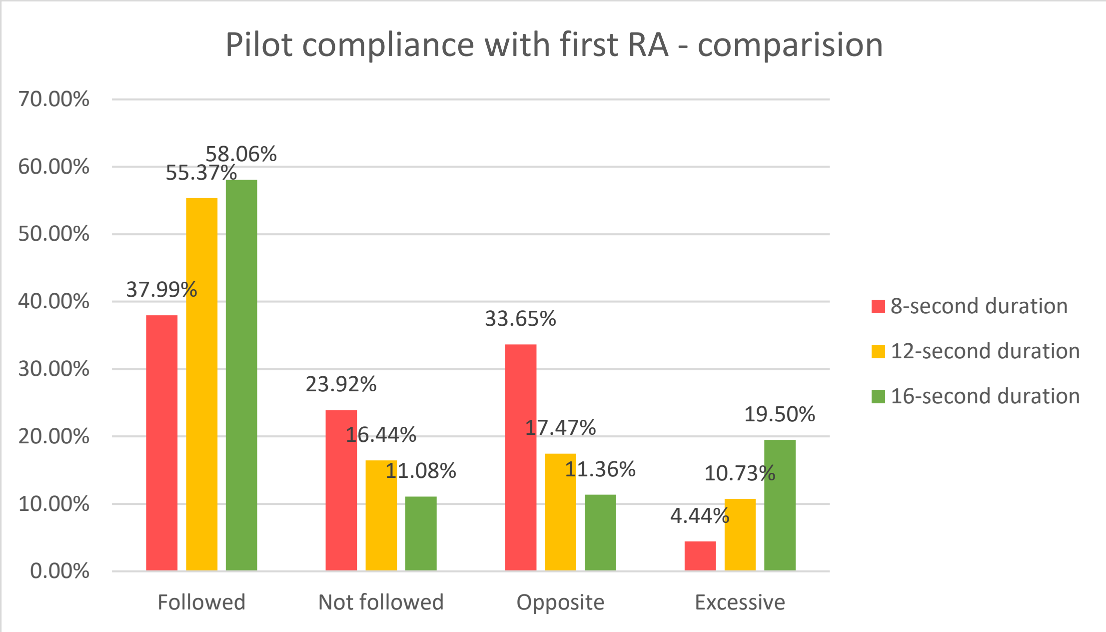


Figure 14. Pilot compliance with first RAs – comparison of the previous results.

The results for each RA type that lasted 16 seconds or longer are presented below.

3.7.1 Climb RA – duration of 16 seconds or longer

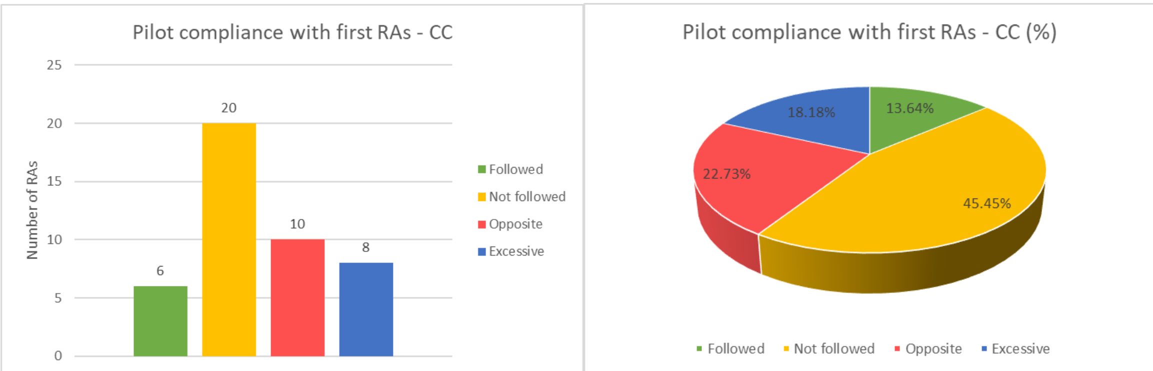


Figure 15. Pilot Compliance with first RAs – CC– 16 seconds or longer.

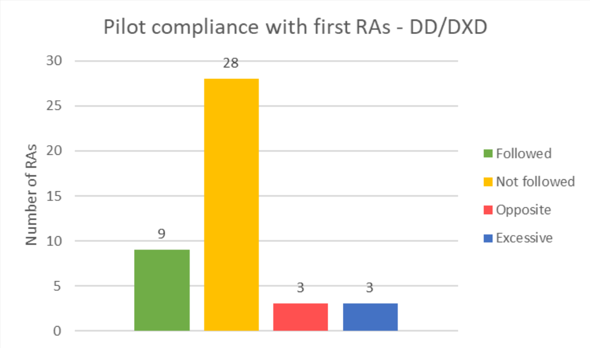
Table 26. Climb RAs – 16-second duration or longer, altitude bands.

Pilot compliance based on altitude – 44 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	0 (0.00)	1 (2.27)	3 (6.82)	0 (0.00)
FL30 - FL100	1 (2.27)	11 (25.00)	6 (13.64)	1 (2.27)
FL100 - FL180	2 (4.55)	4 (9.09)	0 (0.00)	1 (2.27)
FL180 - FL290	2 (4.55)	3 (6.82)	1 (2.27)	3 (6.82)
Above FL290	1 (2.27)	1 (2.27)	0 (0.00)	3 (6.82)

Table 27. Climb RAs duration, 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	84
Average [s]	21.18

3.7.2 Descend RA – duration of 16 seconds or longer



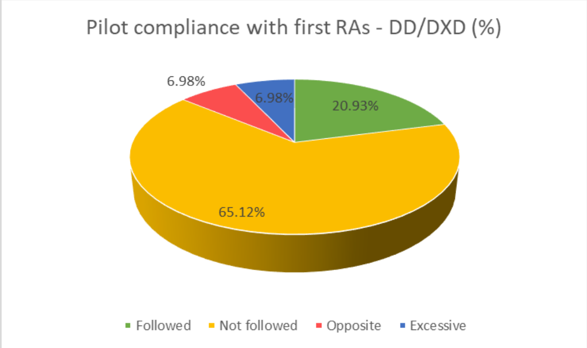


Figure 16. Pilot Compliance with first Descend/Crossing Descend RAs – 16 seconds or longer.

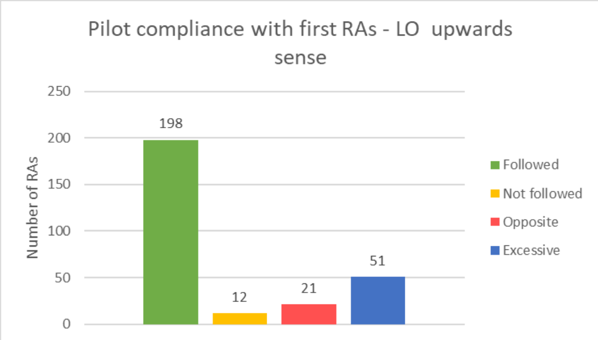
Table 28. Descend/Crossing Descend RAs, 16-second duration or longer, altitude bands.

Pilot compliance based on altitude – 43 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	0 (0.00)	5 (11.63)	0 (0.00)	0 (0.00)
FL30 - FL100	3 (6.98)	15 (34.88)	1 (2.33)	0 (0.00)
FL100 - FL180	1 (2.33)	1 (2.33)	0 (0.00)	0 (0.00)
FL180 - FL290	0 (0.00)	4 (9.30)	1 (2.33)	1 (2.33)
Above FL290	5 (11.63)	3 (6.98)	1 (2.33)	2 (4.65)

Table 29 Descend/Crossing Descend RA duration, 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	100
Average [s]	26.23

3.7.3 Level off RA – upwards sense – duration of 16 seconds or longer



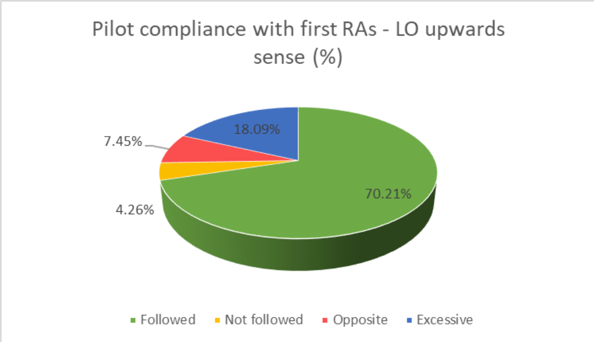


Figure 17. Pilot Compliance with first Level Off upwards RAs – 16 seconds duration.

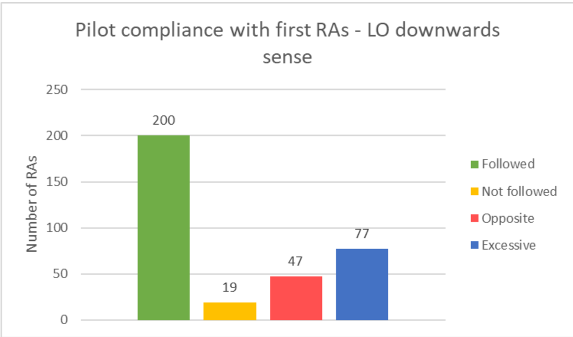
Table 30. Level Off upwards sense RAs – 16-second duration or longer, altitude bands.

Pilot compliance based on altitude –282 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	3 (1.06)	1 (0.35)	0 (0.00)	1 (0.35)
FL30 - FL100	21 (7.45)	1 (0.35)	2 (0.71)	3 (1.06)
FL100 - FL180	29 (10.28)	1 (0.35)	2 (0.71)	4 (1.42)
FL180 - FL290	55 (19.50)	4 (1.42)	8 (2.84)	19 (6.74)
Above FL290	90 (31.91)	5 (1.77)	9 (3.19)	24 (8.51)

Table 31. LO upwards sense RAs duration, 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	204
Average [s]	33.48

3.7.4 Level off RA – downwards sense – duration of 16 seconds or longer



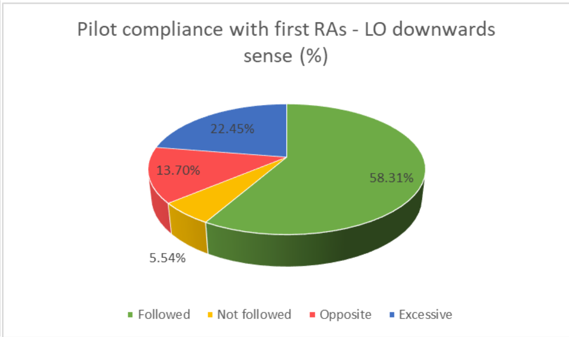


Figure 18. Pilot Compliance with first Level Off downward sense RAs –16 seconds or longer.

Table 32. Level Off downwards sense RAs – 16-second duration or longer, flight levels.

Pilot compliance based on altitude – 343 registered RAs represent 100%				
	Followed (%)	Not followed - too weak (%)	Opposite (%)	Excessive (%)
Below FL30	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
FL30 - FL100	30 (8.75)	8 (2.33)	8 (2.33)	7 (2.04)
FL100 - FL180	17 (4.96)	2 (0.58)	8 (2.33)	6 (1.75)
FL180 - FL290	56 (16.33)	4 (1.17)	13 (3.79)	21 (6.12)
Above FL290	97 (28.28)	5 (1.46)	18 (5.25)	43 (12.54)

Table 33. LO downwards sense RAs duration, 16 seconds duration or longer.

RA duration	
Min [s]	16
Max [s]	316
Average [s]	31.11

3.7.5 Maintain Vertical Speed – duration of 16 seconds or longer

Only 1 Maintain Vertical Speed RAs were observed in the dataset. It occurred between FL30 – FL100 and was followed. Again, the number of Maintain Vertical Speed RAs taken into the assessment is too low to make any significant conclusions.

4 Pilot compliance in relation to Vertical Miss Distances (VMD)

Given the correct pilot responses to Collision Avoidance System instructions, flight safety is increased. In terms of pilot compliance with Resolution Advisories improved safety is obtained by increasing relative altitude between two conflicting aircraft, also known as Vertical Miss Distance. From the TCAS collision avoidance system point of view, the higher VMD is, the better level of safety is achieved.

In the previous section, the focus was on the validation of pilot compliance in terms of vertical speeds achieved during the RA versus the values specified in the IATA/EUROCONTROL Guidance Material. These analyses are very formal and did not provide any insights into safety aspects. In order to broaden the scope of the study, an assessment has been carried out to evaluate the relation between compliance categories and achieved VMD. The aim of the subsequent part of the study is not to determine the detailed level of safety, but to provide with an overall insight how safety, from the TCAS point of view, might be affected depending on pilot compliance with Resolution Advisories.

4.1 Assumptions

- The VMD between two aircraft is measured at the time of the Closest Point of Approach (CPA), which from the safety perspective is the most critical moment during the entire encounter.
- Aircraft, which received more than one RA will not be taken to consideration– the presence of subsequent RAs may have effect on VMD values.
- Only VMDs lower than 1000 ft with the corresponding Horizontal Miss Distance (HMD) lower than 1 NM are considered – the evaluation concentrates on close encounters as they are the most critical in terms of collision avoidance.
- RAs must have lasted at least 8 seconds.

Excessive responses are excluded (as they are unlikely to cause the degradation of the achieved VMD.

4.2 Results

In tables below, each row represents the average value of VMD for *followed*, *not followed* and *opposite* categories.

4.2.1 Vertical Miss Distances for Climb and Descend RAs

Table 34. VMD - Climb RA.

Category	The average of VMDs
Followed	661
Not followed	353
Opposite	294

Table 35. VMD - Descend RAs.

Category	The average of VMDs
Followed	407
Not followed	268
Opposite	65

The correlation between the quality of compliance and vertical miss distances is clear. A 661- and 407-foot separation is achieved when RAs are categorized as *followed* giving the best performance among all three categories. The smallest VMDs were recorded for *opposite* reactions, meaning non-compliance with Climb and Descend RAs may significantly reduce aircraft's relative vertical distance and as a result increase the risk of mid-air collision.

4.2.2 Vertical Miss Distances for Level Off RAs

Table 36. VMD - Level Off upwards sense.

Category	The average of VMDs
Followed	617
Not followed	570
Opposite	573

Table 37. VMD - Level Off, downwards sense.

Category	The average of VMDs
Followed	619
Not followed	519
Opposite	822

There is no significant difference between the VMD values shown in Table 36, unlike the case for the values presented in Table 34 and Table 35. Nonetheless, the highest value is achieved again for the *followed* category. Level Off RAs are typically issued when aircraft are converging with high vertical speed but expected to level off 1000 feet apart according to their ATC clearances (TCAS will issue an RA when it calculates a risk of collision based on the closing speed).

The results attached in Table 37 are susceptible to misinterpretation. As shown to the table, the highest VMD values were achieved for *opposite* reactions. On the basis of the data in the table, the question might be raised whether *opposite* reactions are the safest option in the subject of pilot compliance with Level Off RAs? Such a misleading conclusion could be drawn, but to comprehend this phenomenon correctly, several additional aspects need to be explained. According to the previous analysis, the substantial factor of *opposite* reactions is because pilots' response is far longer than assumed 8-second threshold. The number of *opposite* reactions is significantly reduced each time the minimum time for compliance with RAs is extended (see Table 38).

Table 38. The percentage of opposite RAs - downwards sense.

8-second threshold	12-second threshold	16-second threshold
42.26%	22.31%	13.70%

Most likely, the reason why pilots are reluctant to respond to the RAs immediately is because the majority of aircraft have high vertical rates when the RA is generated. Performing additional calculations shows the average vertical speed, at the time the RA was triggered, was above 2100 ft/min. The vertical profile pictured below illustrates this situation. The compliance occurred later than 20 seconds after the RA was generated.

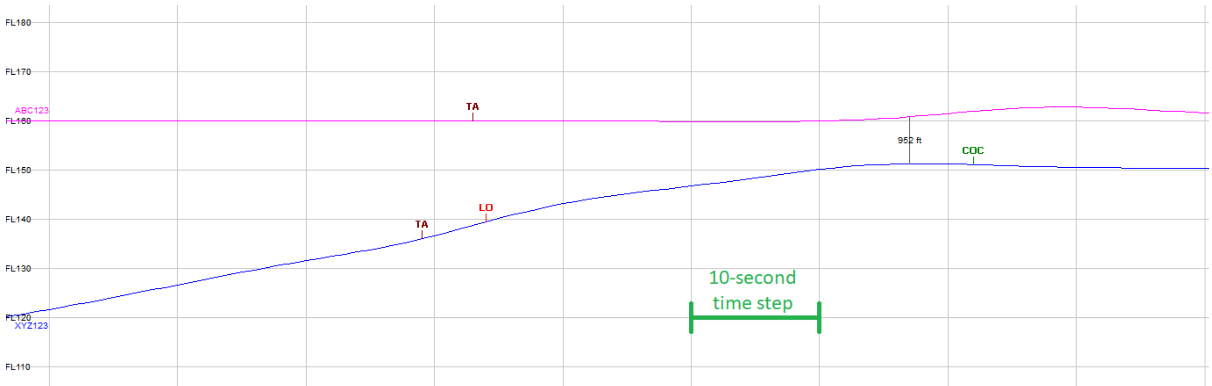


Figure 19. The first example of an RA considered to be not followed.

Investigations showed that the majority of cases classified as *opposite* are similar to the scenario described above. Hence, even if the response was accurate, according to the rigorous time frames specified in the Guidance Material, the response was classified as *opposite* despite a relatively high VMD of 952 ft.

Of course, there are examples of inappropriate compliance, but these scenarios are rather infrequent events and their VMDs are match smaller [Fig. 20].

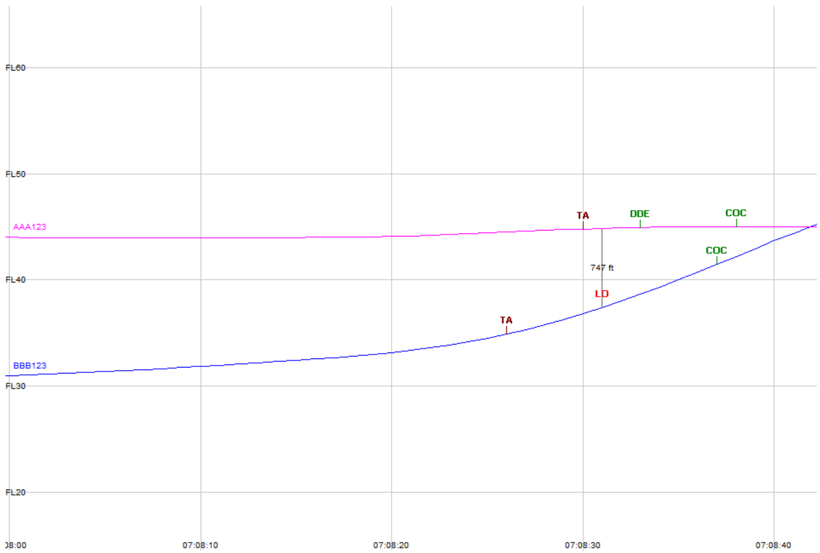


Figure 20. The example of an RA, which is not followed.

5 Conclusions (pilot compliance with TCAS RAs)

The study has shown that a significant proportion of RAs are not flown correctly. These results are line with anecdotal evidence from various sources. The study is 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 (as indicated by simulations of TCAS in safety studies).

The study found a 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 Climb and Descend RAs, regardless of whether the assessment was at 8, 12 or 16 seconds after the RA, the compliance never exceeded 30%, with opposite reactions reaching 22%. Approximately half of the pilots did not achieve the required vertical rate, so their response was classified as “not followed”. It should be noted here that the required vertical rate was “generously” applied, classifying an RA as followed if the vertical speed was within 300 ft/min. of the required vertical rate (as indicated by the lowest value of the green arc).

Prompt and correct responses are particularly important for reversal and strengthening RAs. Unfortunately, in over half of the cases pilots did not react correctly to these RAs. Although the assessment using radar data comes with some limitations (which could be overcome with the use of recorded airborne data, but this is not generally available due to logistic, commercial, and legal reasons), it clearly indicates that the level of pilot compliance with TCAS resolution advisories is low. That, again, emphasises the need for aircraft operators to monitor carefully performance of their crews and to take corrective measures as necessary.

Based on the VMDs conducted examination it can be confirmed that pilot compliance with Resolution Advisories brings safety benefits by increasing the relative vertical distance between the two conflicting aircraft.

Abbreviations

ACAS – Airborne Collision Avoidance System
ATC – Air Traffic Control
BDS – Comm-B Data Selector
CC – Climb RA
COC – Clear of Conflict
CCN – Reversal Climb RA
CXC – Crossing Climb RA
CPA – closest point of approach
DD – Descend RA
DDN – Reversal Descend RA
DXD – Crossing Descend RA
HMD – Horizontal Miss Distance
IATA – International Air Transport Association
IC – Increase Climb RA
ID – Increase Descent RA
ICAO – International Civil Aviation Organization
LO – Level Off RA
MEL – Minimum Equipment List
MVS – Monitor Vertical Speed RA
MVSCM – Maintain Vertical Speed Crossing Maintain RA
MVSM – Maintain Vertical Speed RA
NMAC – Near Mid-Air Collision
RA – Resolution Advisories
TA – Traffic Advisory
TCAS – Traffic Alert and Collision Avoidance System
VMD – Vertical Miss Distance

Glossary

Multi-threat encounter – a type of encounter where more than two aircraft are involved.

Near Mid-air Collision (NMAC) – Two aircraft simultaneously coming within 100 feet vertically and 500 feet (0.08 NM) horizontally.

Reversed sense RA – an RA type, which has its sense reversed in the opposite direction to the previous one.

Strengthening RAs – an RA type, which increases the strength of the previously issued RA. For example, an initial positive RA (which requires either climb or descend) can be strengthened to either Increase Climb or Increase Descent RAs.

Weakening RA – an RA type generated in order to reduce vertical deviation from initial path induced by an initial RA.