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EUROCONTROL

THE ASSESSMENT OF PILOT COMPLIANCE WITH TCAS RAs, TCAS MODE SELECTION AND SERVICEABILITY USING ATC RADAR DATA

Edition Number : 2.2
Edition Validity Date : 10/02/2022

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DOCUMENT CHARACTERISTICS

Document Title	Document Subtitle (optional)	Edition Number	Edition Validity Date
The assessment of pilot compliance with TCAS RAs, TCAS mode selection and serviceability using ATC radar data		2.2	10/02/2022

Abstract

The main purpose of this document is to present the result of an assessment of pilot compliance with TCAS RAs, TCAS mode selection and TCAS serviceability. Radar recordings from core European airspace were used to conduct this assessment. Analysis indicates that resolution advisories are often not flown correctly. Moreover, a number of aircraft operate daily in core European airspace with TCAS out of service or with TCAS in a TA-only mode. In all these cases TCAS does not offer the intended collision avoidance protection.

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STATUS AND ACCESSIBILITY

Status		Accessible via	
Working Draft	☐	Intranet	☒
Draft	☐	Extranet	☐
Proposed Issue	☐	Internet (www.eurocontrol.int)	☐
Released Issue	☒		

TLP STATUS

Intended for		Detail
Red	☐	Highly sensitive, non-disclosable information
Amber	☐	Sensitive information with limited disclosure
Green	☒	Normal business information
White	☐	Public information

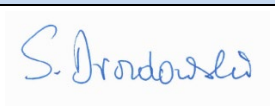
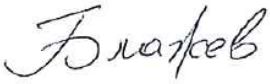
DOCUMENT APPROVAL

The following table identifies all management authorities who have successively approved the present issue of this document.

This table may be replaced by a format document review and approval meeting, with the meeting details recorded and retained that edition's archive folder.

The approval may also be recorded via electronic workflow, where put in place.

Where document approval is made via a meeting or electronic workflow, the details shall be indicated here in place of the approval table.

AUTHORITY (Name and function)	SIGNATURE	DATE
Stan Drozdowski NMD/SAF		10/02/2022
Tzvetomir Blajev NMD/SAF		10/02/2022
Antonio Licu, Head of NMD/SAF (endorses)		10/02/2022
Iacopo Prissinotti, Director NMD (accepts)		11/02/2022

Edition History

The following table records the complete history of the successive editions of the present document.

Edition No.	Edition Validity Date	Author	Reason
0.9	06/07/2020	Mateusz Michalski; Stanislaw Drozdowski	Document created
0.91	14/07/2020	Mateusz Michalski; Stanislaw Drozdowski	Internal review, editorial changes.
1.0	01/10/2020	Stanislaw Drozdowski	SAFOPS review. Ready for release.
2.0	15/02/2021	Stanislaw Drozdowski	SAFOPS comments incorporated and another assessment method (*Method B)* added. Assessment for various aircraft types and type of operations added. Minor corrections of the previously published results (rounding errors, duplicated encounters removed, etc.).
2.01	05/03/2021	Stanislaw Drozdowski	Editorial corrections: Table 2-2: typo (8135 -> 813) Page 75: typo (Turbojets -> Turboprops) Table 4-13: overlapping labels Page 77: white space removed
2.1	09/04/2021	Stanislaw Drozdowski	Section 5.5 added Conclusions (Section 8) modified to include the data contained in Section 5.5
2.2	10/02/2022	Stanislaw Drozdowski	Section 9 expanded to provide additional data. Hyperlinks and references updated.

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Executive Summary

TCAS RA not followed is one of Top 5 ATM operational risk priorities. To supplement the previously conducted studies, a study of pilot compliance with TCAS Resolution Advisories has been carried out.

The purpose of the document:

- To evaluate the performance of pilot responses to advisories generated by TCAS (sections 2 through 7);
- To assess TCAS operating mode selection and serviceability (sections 8 and 9).

Methodology:

- Obtaining the set of radar data from core European airspace, over the period of 12 months,
- Processing the radar data and evaluating aircraft's vertical rates based on the IATA/EUROCONTROL's Guidance Material and an alternative method which takes into account pilot's ability of a pilot to respond promptly, for example, to a Climb RA whilst in descent.

Key findings:

- In total, 1176 RAs were examined,
- A substantial number of RAs were not followed correctly,
- Compliance varied depending on RA type and duration, as well as the method used to assess RA compliance; in the worst cases the correct compliance was achieved in a third of encounters,
- No significant performance differences were observed while comparing crews of EASA-country registered aircraft vs non-EASA aircraft as well as between different aircraft types,
- Airline pilots are generally better at compliance with the RA than other operations (cargo, military, and business jets),
- Based on the assessment of VMDs it can be confirmed that pilot compliance with Resolution Advisories brings safety benefits by increasing the relative vertical distance between the two conflicting aircraft.

These results are in line with the previously conducted research.

It has been observed that compliance with some RA type improved if the RA lasted 12 seconds or longer. However, corrective Climb and Descend RA were frequently not followed correctly regardless of their duration.

The examination of Vertical Miss Distance at the Closest Point of Approach shows that for RAs that were followed correctly, the level of safety (from the TCAS perspective) has been improved. Conversely, for RA that were not followed correctly a deterioration of the achieved Vertical Miss Distance (and, consequently, safety) has been observed.

In some cases, the sample size was too low to determine reliably whether the observed result occurred by chance or was a sign of a systemic problem.

A supplementary assessment of *TCAS operating mode selection and serviceability* (sections 8 and 9) showed that some aircraft operate without serviceable TCAS or with the TCAS mode incorrectly selected. Although the number of such flights is relatively low, these flights by being virtually unequipped increase the global risk for the network.

1 Objective

The main purpose of this document is to present the result of an assessment of pilot compliance with TCAS RAs, TCAS mode selection and TCAS serviceability.

As specified in EU Regulation 2019/123, the Network Manager is tasked with identifying operational safety hazards at European ATM network level and to assess the associated network safety risk. To fulfil this obligation, the Network Manager implemented a dedicated risk identification and monitoring process.

The current ATM Top 5 operational risk priorities are:

- Blind spot (conflict between aircraft in close proximity not detected by air traffic controller);
- TCAS RA not followed;
- Flight without a transponder or with a dysfunctional one;
- Detection of potential runway conflict by air traffic controllers;
- Sudden, high energy runway conflict.

This study has been carried out to help address the "TCAS RA not followed[1]" operational risk in order to provide operational data assessing pilot responses to TCAS RAs, as well as TCAS operational mode and serviceability. This study supplements the survey conducted in 2017[2] in which a significant number of pilots admitted that RAs are often not followed. Also, previous monitoring activities established that pilots often do not follow RAs correctly[3].To conduct this study, radar recordings from core European airspace[4] were analysed. The results are in line with the previous studies.

Moreover the same data set indicates that a number of aircraft operate daily in core European airspace with TCAS out of service or with TCAS in a TA-only mode. Therefore, in all these cases, TCAS II does not offer the intended collision avoidance protection. The study did not look into the reasons for non-compliance, which should be researched separately.

[1] See SKYbrary article.

[2] Available on SKYbrary.

[3] EVAIR Safety Bulletin no 14 (2010-2014).

4 Airspace in western and central part of Europe where traffic density is high.

2 Introduction

2.1 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. Furthermore, a subset of the data was used to assess TCAS operating mode selection and serviceability. The results of this assessment are described in sections 9 and 10.

Following the release of version 1.0 of this report on 1st October 2020, the data set and calculations were reviewed. The review resulted in some adjustment in the calculations as well as the removal of some duplicate encounters as well as some corrections to intermediate RA compliance calculations, which resulted in small amendments to the results presented in section 4.

In this version of the report an alternative approach to measuring pilot compliance was devised; this new method takes into consideration the vertical rate at the start of the RA, pilot reaction time, and limits on aircraft acceleration. Both the original approach and the new approach to pilot compliance are presented in this report. They are referred to as *Method A* and *Method B*, respectively. *Method A* follows the IATA/EUROCONTROL's Guidance Material[5] while the *Method B* algorithm is described in detail in Annex 1.

Furthermore, additional pilot compliance results are presented in this report in section 7, broken down according to various criteria, including EASA / non-EASA country of aircraft registration, the type of operation, and the aircraft type group or family.

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 2-1): altogether 1256 initial RAs were recorded in 1084 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.

[5] IATA/EUROCONTROL Guidance Material on Performance assessment of pilot compliance to Traffic Alert and Collision Avoidance System (TCAS) using Flight Data Monitoring (FDM) is available from IATA via SKYbrary.

Table 2-1. The final number of encounters and RAs taken into the assessment.

Total encounters with at least one aircraft having single RA	1084
The total number of all first RAs	1256
The total number of all RAs	1503
Coordinated encounters (i.e. both aircraft get an RA)	172
Uncoordinated encounters (1 aircraft receiving RA)	912
Encounters against Mode S intruders	1041
Equipped – Mode A/C encounters	43

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), corrupted or inconsistent were filtered out. Further analysis of the 1180 RAs of duration of 8 seconds or more was carried out. Some of these RAs, as shown in Table 2-2 below, lasted for 12 seconds or longer (1004) or 16 seconds or longer (813).

In 169 cases the first RA changed (i.e. either strengthened, reversed or weakened) and in a further 19 cases there was at least one further RA change.

Table 2-2. 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	1176
1st RAs analysed – a total duration of each RA lasted for 12 seconds or longer	1004
1st RAs analysed – a total duration of each RA lasted for 16 seconds or longer	813
2nd RAs analysed – a total duration of each RA lasted for 8 seconds or longer	169
2nd RAs analysed – a total duration of each RA lasted for 12 seconds or longer	129
2nd RAs analysed – a total duration of each RA lasted for 16 seconds or longer	99
3rd and more RAs analysed – a total duration of each RA lasted for 8 seconds or longer	19
3rd and more RAs analysed – a total duration of each RA lasted for 12 seconds or longer	15
3rd and more RAs analysed – a total duration of each RA lasted for 16 seconds or longer	9

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 0.25*g*, see ICAO ACAS Manual (Doc. 9863). Using ICAO's standard pilot model, it can been calculated that the pilots may not be able to achieve the RA required vertical rate within the 8-second period. For example, in a situation in which a level aircraft receives a Descend RA, an acceleration of 0.25g will necessitate a duration of 3.1 seconds to achieve the required vertical rate of -1500 ft/min. This, together with a pilot reaction time of 5 seconds, means that the required vertical rate will not quite be achieved by 8 seconds – even more so if the aircraft has a positive vertical rate when the Descend RA was generated. 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.

2.2 RA types

In order to provide the Reader with a higher level of detail regarding the recorded RAs, the RA names not providing their vertical sense have been amended to indicate the sense, e.g. for a Level Off RA while climbing a "LO (DN)" abbreviation is used rather than usual "LO" or MVS (LCL) instead of MVS.

Level Off RAs (LO) always require a reduction of the vertical speed to 0 ft/min., i.e. a level off. A Level Off RA can be issued in Upward Sense[6] or Downward Sense[7].

For initial RAs or some subsequent RAs (strengthening RAs):

- a LO (UP) (Level Off Upward Sense RA) is typically issued while the aircraft is descending and will prohibit any further descent by displaying the red arc (zone) below zero on the cockpit instruments;
- a LO (DN) (Level Off Downward Sense RA) RA is typically issued while the aircraft is climbing and will prohibit any further climb by displaying the red arc (zone) above zero on the cockpit instruments.

For **weakening RAs** (issued to limit a deviation from the cleared level when the previously issued RA has already provided sufficient separation):

- a LO (UP) (Level Off Upward Sense RA) is issued when a climb (required by the previous RA) is no longer needed and will prohibit any further climb by displaying the red arc (zone) above zero on the cockpit instruments;
- a LO (DN) (Level Off Downward Sense RA) is issued when a descent (required by the previous RA) is no longer needed and will prohibit any further descent by displaying the red arc (zone) below zero on the cockpit instruments.

[6] RA downlink bit 43 = 0

[7] RA downlink bit 43 = 1

Monitor Vertical Speed RAs (MVS) are preventive RAs[8] that prohibit certain vertical rates (0, 500, 1000, 2000 ft/min.) either for climb or descent (the value of the prohibited vertical speeds is not available in the RA downlink messages). Here, these RAs are referred to as MVS (LCL) (Limit Climb)[9] for RAs prohibiting any climb rates or MVS (LDE) (Limit Descent)[10] for RAs prohibiting any descent rates.

Maintain Vertical Speed RAs that require the aircraft to continue the current climb are referred to as MaVS (CL)[11] while the RAs that require the aircraft to continue the current descent are referred to as MaVS (DE)[12].

The list all RA abbreviations is shown in Table 2-3. Some RAs were not recorded during this study and they are listed here only for completeness. RAs marked with an asterisk (*) are only possible as a subsequent RA, not as the first RA in the encounter.

Table 2-3. Abbreviations of RA types.

Abbreviation	RA
CL	Climb
DE	Descend
XCL	Crossing Climb
XDE	Crossing Descend
ICL *	Increase Climb *
IDE *	Increase Decent *
RCL *	Reversal Climb *
RDE *	Reversal Decent *
LO (UP)	Level Off (upward sense)
LO (DN)	Level Off (downward sense)
MaVS (CL)	Maintain Vertical Speed (while climbing)
XMaVS (CL)	Crossing Maintain Vertical Speed (while climbing)
MaVS (DE)	Maintain Vertical Speed (while descending)
XMaVS (DE)	Crossing Maintain Vertical Speed (while descending)
MVS (LCL)	Monitor Vertical Speed (limit climb)
MVS (LDE)	Monitor Vertical Speed (limit descent)
COC	Clear of Conflict (RA termination)

Other abbreviations used in this document can be found in section 11.1. A Glossary of Terms and a list of references are provided in sections 11.2 and 11.3 respectively.

[8] An RA that instructs the pilot to avoid certain deviations from current vertical rate,

[9] RA downlink bit 43 = 1

[10] RA downlink bit 43 = 0

[11] RA downlink bit 43 = 0

[12] RA downlink bit 43 = 1

3 Limitations and assumptions

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

- Data used in calculations outlined this document has been obtained through ATC radar recordings. Radar data is in turn processed by ATC trackers every 4 seconds. Additionally, some latency may also be caused by rotation of a radar antenna. 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 (as per the European mandate);
- Two separate approaches were taken to assess pilot compliance; *Method A* examined the vertical rates of aircraft after the RA and compared these against the thresholds published in the IATA/EUROCONTROL Guidance Material; Essentially, *Method A* followed the IATA/EUROCONTROL Guidance Material strictly. *Method B*, on the other hand, was based on the same guidance material, but also took a reaction time (5 seconds) by the pilot into account, as well as a 0.25*g* expected limit on acceleration. In effect *Method B*, gives credit to a pilot having to significantly change vertical rate (e.g. from climb to descent) even if the final required vertical rate has not yet been met.
- 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.
- In some cases, the sample size was too low to determine reliably whether the observed result occurred by chance or was a sign of a systemic problem.

The pilot compliance results are presented for *Method A* in section 4, and for *Method B* in section 5.

4 Assessment Results: *Method A*

The results described in this section were previously published in version 1.0 (dated 1st October 2020). In this current version, the values presented in the text, tables and graphs have been adjusted to reflect the assessment after the removal of some duplicate encounters, as well as some minor corrections to the intermediate calculations.

Based on the IATA/EUROCONTROL Guidance Material, pilot responses for *Method A* 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 compared 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.

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

As shown below in Table 4-1, in the set of 1176 RAs the majority of RAs (65%) 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 RAs "not followed" 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 are shown in Table 4-1 and Figure 4-1 below.

Table 4-1. All types of first RAs – 8 seconds or longer.

First RA – an 8-second duration or longer					
	Followed	Not followed - too weak	Opposite	Excessive	The total number of each RA type (100%=1176)
Climb	33 (22%)	85 (58%)	26 (18%)	4 (3%)	148 (13%)
Descend/Crossing Descend	31 (25%)	79 (65%)	7 (6%)	5 (4%)	122 (10%)
Level Off – Upward sense	147 (42%)	41 (12%)	143 (41%)	22 (6%)	353 (30%)
Level Off – Downward sense	177 (44%)	42 (10%)	172 (43%)	15 (4%)	406 (35%)
Maintain Vertical Speed	3 (99%)	0 (0%)	0 (0%)	0 (0%)	3 (1%)
Monitor Vertical Speed	Not assessed				144 (12%)
Total	391 (38%)	247 (24%)	348 (34%)	46 (5%)	

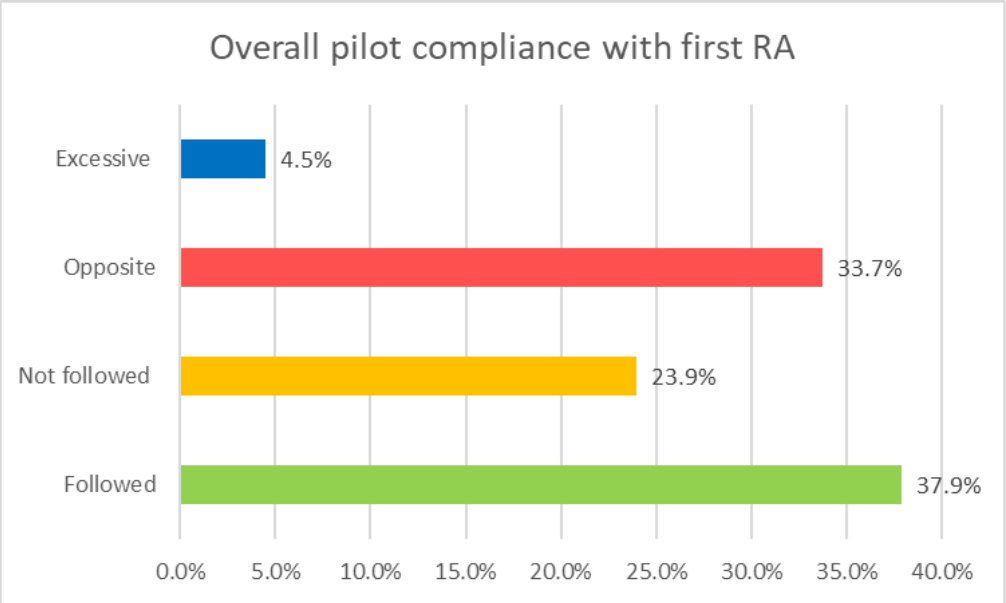

Figure 4-1. Pilot compliance with first RAs (%) – 8 seconds or longer.

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

4.1.1 Climb RAs – duration of 8 seconds or longer

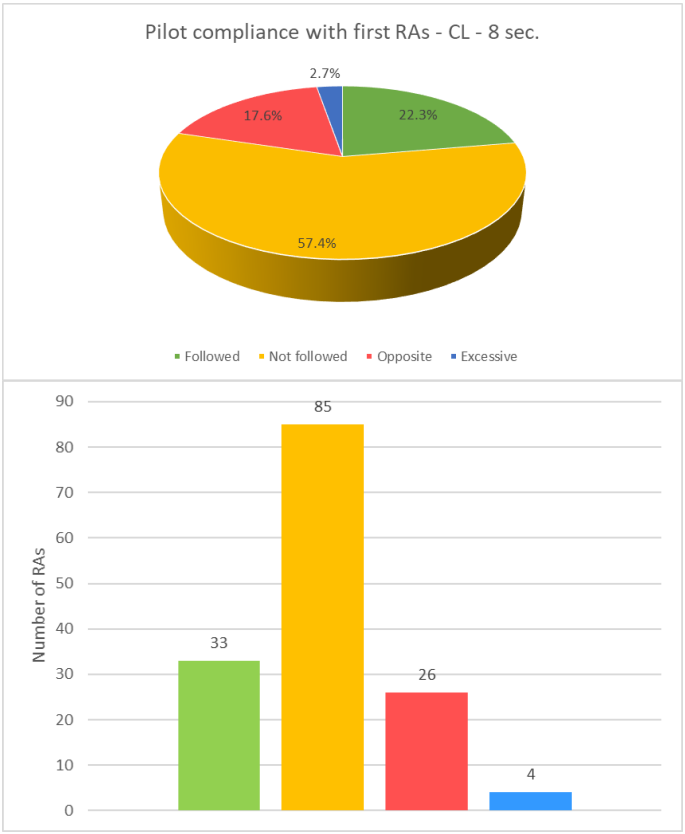

Figure 4-2.Pilot Compliance with first Climb RAs – 8 seconds or longer.

Table 4-2. Climb RAs – an 8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 148 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	3 (27%)	2 (18%)	6 (55%)	0 (0%)
FL30 - FL100	8 (16%)	29 (58%)	12 (24%)	1 (2%)
FL100 - FL180	9 (38%)	13 (54%)	2 (8%)	0 (0%)
FL180 - FL290	9 (25%)	21 (60%)	4 (12%)	1 (3%)
Above FL290	4 (14%)	20 (72%)	2 (7%)	2 (7%)

Table 4-3. Climb RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	84
Average [s]	13.1

Table 4-2 shows the RA compliance rate as percentages per Flight Level band. Generally, it is held 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 were even flown in the opposite direction at higher altitudes, contradicting this belief.

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

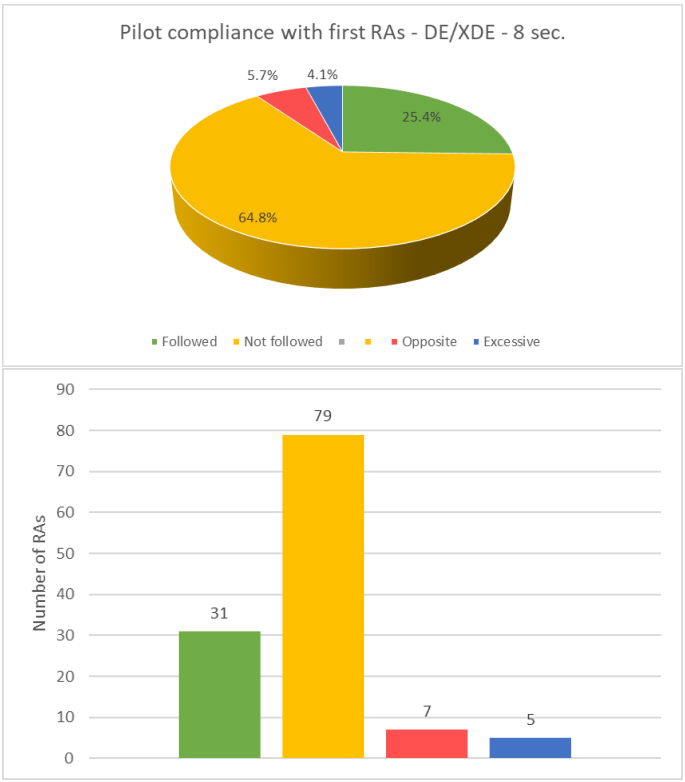

Figure 4-3. Pilot Compliance with first Descend/Crossing Descend RAs – 8 seconds or longer.

Table 4-4. 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 (22%)	6 (67%)	1 (11%)	0 (0%)
FL30 - FL100	16 (43%)	15 (41%)	5 (13%)	1 (3%)
FL100 - FL180	0 (0%)	5 (83%)	1 (17%)	0 (0%)
FL180 - FL290	6 (20%)	23 (77%)	0 (0%)	1 (3%)
Above FL290	7 (17%)	30 (75%)	0 (0%)	3 (7%)

Table 4-5. Descend/Crossing Descend RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	100
Average [s]	15.9

Similarly to Climb RAs, very few Descend and Crossing Descend RAs were followed correctly regardless of the altitude band (see Table 4-4). Three quarters of Descend RAs were not followed in the highest altitude band. There were only a few opposite or excessive reactions to Descend RAs.

4.1.3 Level off upward sense RAs – duration of 8 seconds or longer.

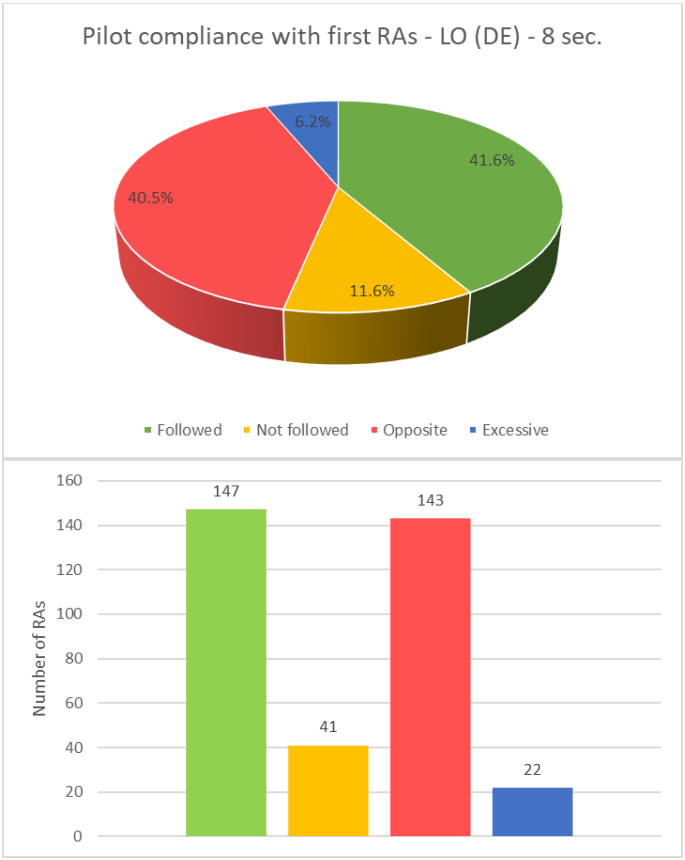

Figure 4-4. Pilot compliance with first RAs – Level off upward sense – 8 seconds or longer.

Table 4-6. Level off upward sense RAs – an 8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 353 registered RAs represents 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	2 (33%)	0 (0%)	3 (50%)	1 (17%)
FL30 - FL100	20 (44%)	4 (9%)	18 (40%)	3 (7%)
FL100 - FL180	23 (50%)	9 (20%)	11 (24%)	3 (6%)
FL180 - FL290	42 (37%)	9 (8%)	53 (47%)	9 (8%)
Above FL290	60 (42%)	19 (13%)	58 (41%)	6 (4%)

Table 4-7. Level Off upward sense RAs duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	204
Average [s]	28.7

4.1.4 Level off downward sense RAs – duration of 8 seconds or longer

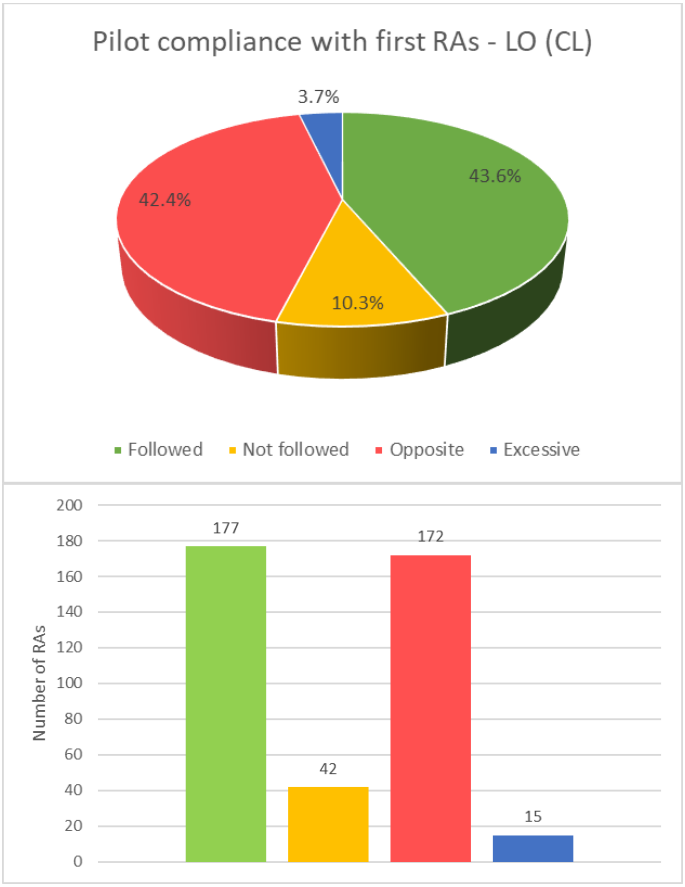

Figure 4-5. Pilot Compliance with first Level Off downward sense RAs – 8 seconds or longer.

Table 4-8. Level Off downward sense RAs – 8-second duration or longer, altitude bands.

Pilot compliance based on altitude – 406 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	0 (0%)	1 (100%)	0 (0%)	0 (0%)
FL30 - FL100	22 (34%)	5 (8%)	37 (57%)	1 (1%)
FL100 - FL180	15 (35%)	2 (5%)	24 (55%)	2 (5%)
FL180 - FL290	39 (37%)	17 (16%)	44 (41%)	6 (6%)
Above FL290	101 (53%)	17 (9%)	67 (35%)	6 (3%)

Table 4-9. Level Off downward sense RAs Duration – 8 seconds or longer.

RA duration	
Min [s]	8
Max [s]	316
Average [s]	27.8

4.1.5 Maintain Vertical Speed RAs – duration of 8 seconds or longer

Only 3 Maintain Vertical Speed RAs were observed in the dataset. All 3 occurred below FL180 and were followed. However, this number is too low to assess pilot compliance with any statistical confidence.

4.2 Secondary RAs – duration of 8 seconds or longer

During the course of an encounter, TCAS evaluates the RA strength 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 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 169 cases (see Table 4-10), 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 (ostensibly 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 4-10. All types of secondary RAs – 8 seconds or longer.

Secondary RA – an 8-second duration or longer					
	Followed	Not followed - too weak	Opposite	Excessive	The total number of each RA type (100% = 169)
Climb	3 (30%)	6 (50%)	2 (20%)	0 (0%)	11 (6%)
Reversal Climb	0 (0%)	1 (50%)	1 (50%)	0 (0%)	2 (1%)
Increase Climb	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Descend/Crossing Descend	3 (30%)	7 (60%)	1 (10%)	1 (10%)	12 (7%)
Reversal Descend	2 (67%)	0 (0%)	0 (0%)	1 (33%)	3 (3%)
Level Off – upward sense	41 (50%)	1 (1%)	3 (4%)	37 (45%)	82 (48%)
Level Off – downward sense	29 (52%)	0 (0%)	1 (2%)	26 (46%)	56 (33%)
Maintain Vertical Speed	2 (100%)	0 (0%)	0 (0%)	0 (0%)	2 (1%)
Total	81 (48%)	15 (9%)	8 (5%)	65 (38%)	

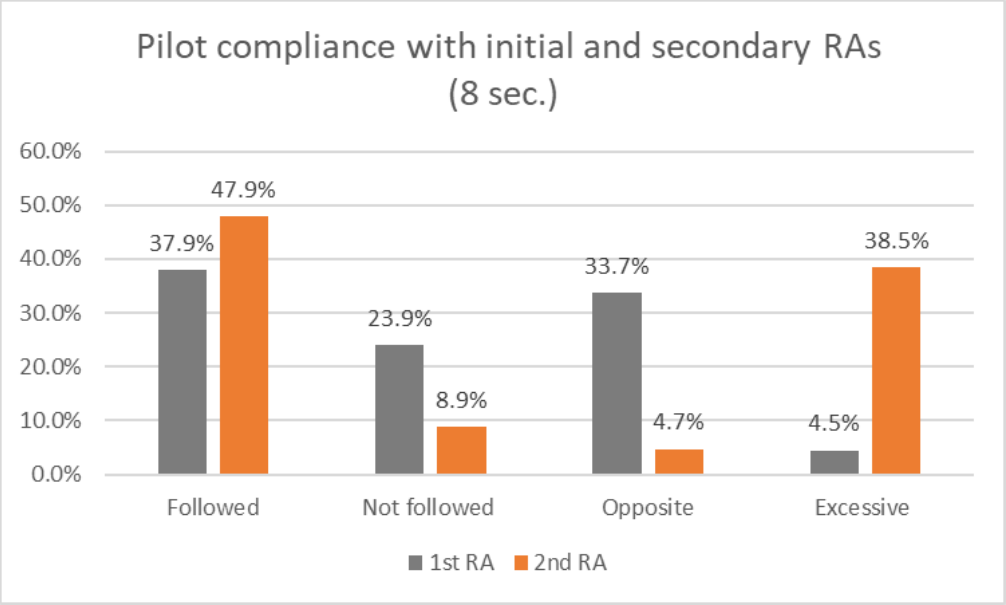

Figure 4-6. Pilot compliance with initial and secondary RAs – 8 seconds or longer.

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

Only 19 RAs subsequent to a secondary RA were recorded in the dataset (see Table 4-11). The number is not sufficient to conduct any meaningful analysis on this subset of data.

Table 4-11. All types of third and subsequent RAs – 8 seconds or longer.

Third and subsequent RAs – an 8-second duration or longer					
Type	Followed	Not followed - too weak	Opposite	Excessive	Total
Climb/Reversal Climb	1	0	0	0	1
Descend/Crossing Descend/Reversal Descend	0	1	1	0	2
Level Off – upward sense	2	0	0	2	4
Level Off – downward sense	4	0	0	5	9
Maintain Vertical Speed Maintain	1	0	0	0	1
Monitor Vertical Speed	Not Assessed				2
Total	9	2	0	7	18

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

Out of 1176 first RAs, 1004 (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 4-12. All types of first RAs – 12 seconds or longer.

First RA - an 12-second duration or longer					
	Followed	Not followed - too weak	Opposite	Excessive	The total number of each RA type (100%=1004)
Climb	19 (21%)	50 (55%)	15 (16%)	7 (8%)	91 (9%)
Descend/Crossing Descend	27 (31%)	53 (60%)	5 (6%)	3 (3%)	88 (8%)
Level Off – upward sense	216 (68%)	22 (7%)	49 (15%)	33 (10%)	320 (32%)
Level Off – downward sense	219 (58%)	22 (6%)	83 (22%)	51 (14%)	375 (37%)
Maintain Vertical Speed	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Monitor Vertical Speed	Not assessed				129 (13%)
Total	482 (55%)	147 (17%)	152 (17%)	94 (11%)	

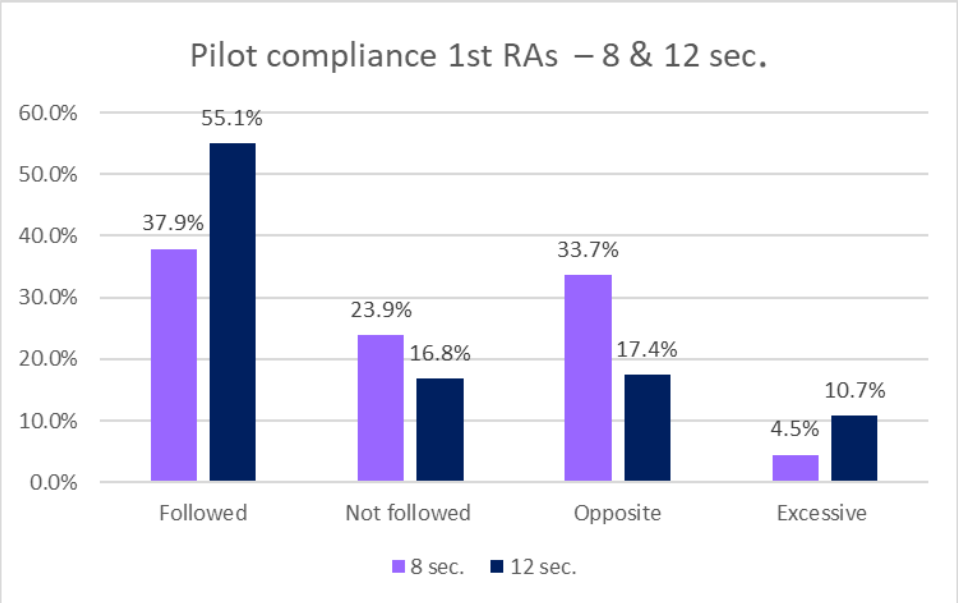

Figure 4-7. Pilot compliance with first RAs – comparison after 8 and after 12 sec.

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

4.4.1 Climb RAs – duration of 12 seconds or longer

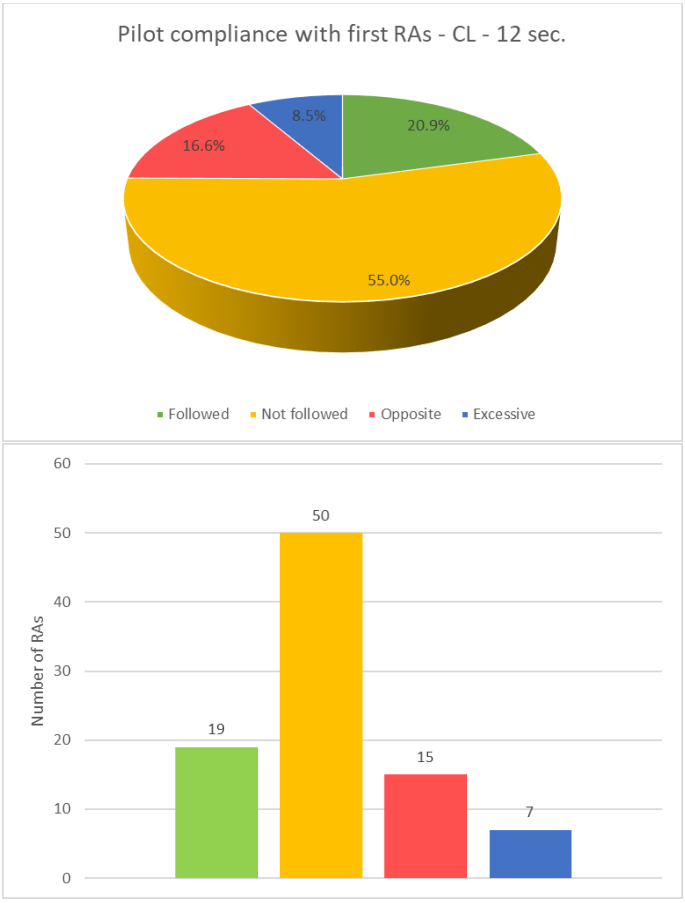

Figure 4-8. Pilot Compliance with first Climb RAs – 12 seconds or longer.

Table 4-13. Climb RAs – 12- second duration or longer, altitude bands.

Pilot compliance based on altitude – 91 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	1 (14%)	3 (43%)	3 (43%)	0 (0%)
FL30 - FL100	4 (12%)	20 (58%)	9 (26%)	1 (3%)
FL100 - FL180	5 (42%)	4 (33%)	2 (17%)	1 (8%)
FL180 - FL290	4 (20%)	13 (65%)	0 (0%)	3 (15%)
Above FL290	5 (27%)	10 (56%)	1 (6%)	2 (11%)

Table 4-14. Climb RAs duration – 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	84
Average [s]	16.3

4.4.2 Descend/Crossing Descend RAs – duration of 12 seconds or longer

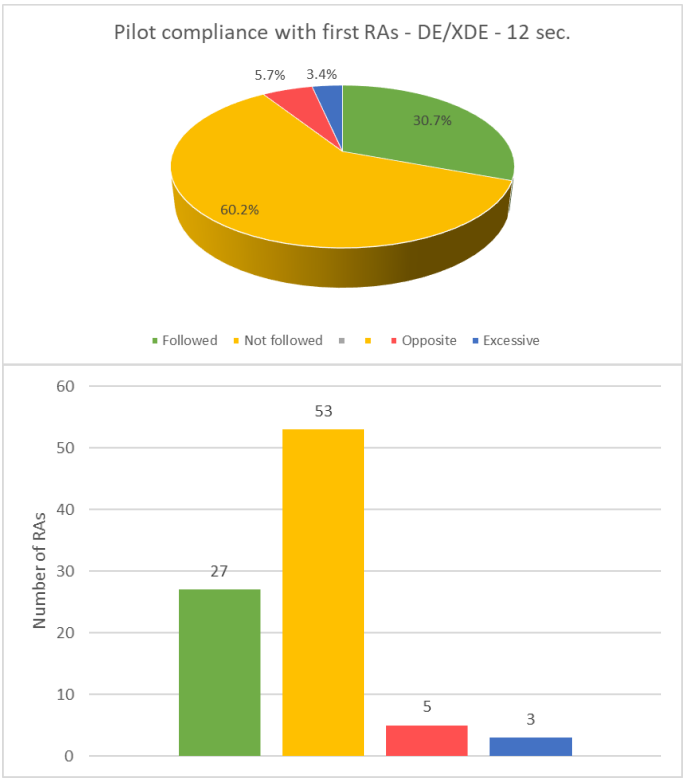

Figure 4-9. Pilot Compliance with first RAs – Descend/Crossing Descend – 12 seconds or longer.

Table 4-15. 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 (14%)	6 (86%)	0 (0%)	0 (0%)
FL30 - FL100	9 (33%)	15 (56%)	3 (11%)	0 (0%)
FL100 - FL180	2 (33%)	3 (50%)	1 (17%)	0 (0%)
FL180 - FL290	7 (32%)	14 (64%)	1 (4%)	0 (0%)
Above FL290	8 (31%)	15 (58%)	0 (0%)	3 (11%)

Table 4-16.Descend/Crossing Descend RAs duration – 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	100
Average [s]	19

4.4.3 Level off upward sense RAs – duration of 12 seconds or longer

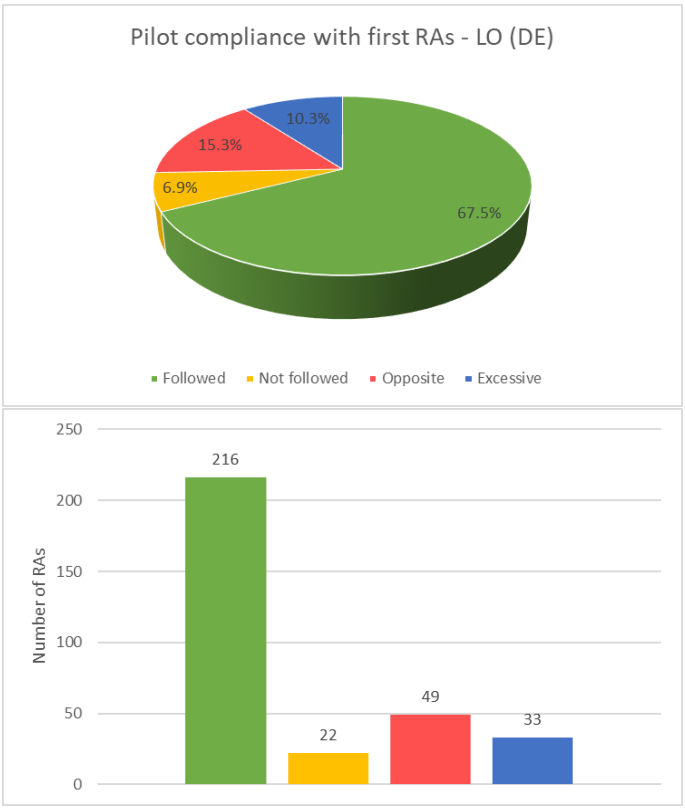

Figure 4-10. Pilot Compliance with first RAs – LO upward sense – 12 seconds or longer.

Table 4-17. Level Off upward sense – 12-second duration or longer, altitude bands.

Pilot compliance based on altitude – 320 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	2 (40%)	1 (20%)	1 (20%)	1 (20%)
FL30 - FL100	23 (66%)	2 (6%)	8 (22%)	2 (6%)
FL100 - FL180	35 (82%)	1 (2%)	4 (9%)	3 (7%)
FL180 - FL290	63 (62%)	9 (9%)	17 (17%)	13 (12%)
Above FL290	93 (69%)	9 (7%)	19 (14%)	14 (10%)

Table 4-18. Level Off upward sense RAs duration – 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	204
Average [s]	31

4.4.4 Level off downward sense RAs – duration of 12 seconds or longer

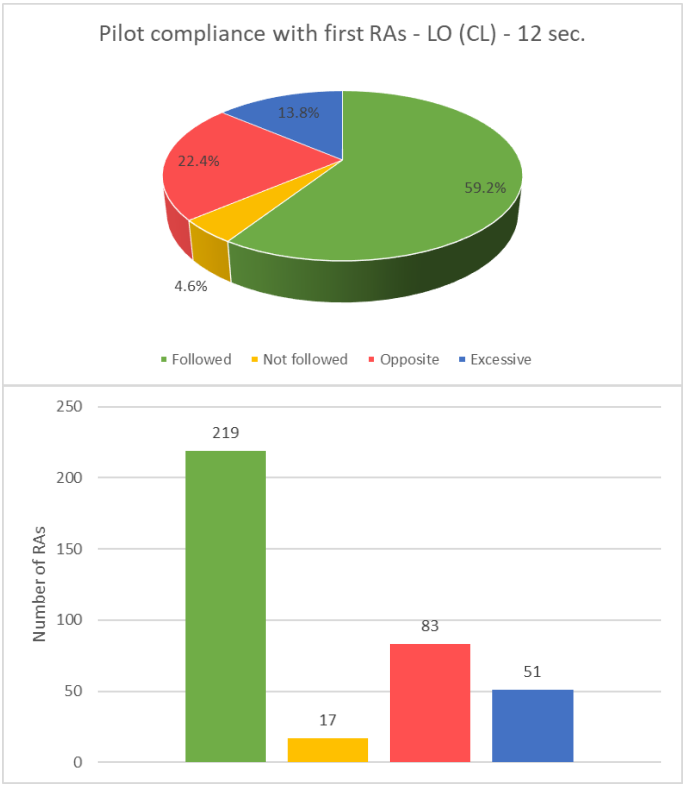

Figure 4-11.Pilot Compliance with first Level Off downward sense RAs –12 seconds or longer.

Table 4-19. Level Off downward sense RAs – 12-second duration or longer, altitude bands.

Pilot compliance based on altitude – 375 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	0 (0%)	0 (0%)	1 (100%)	0 (0%)
FL30 - FL100	31 (54%)	6 (10%)	18 (32%)	2 (4%)
FL100 - FL180	18 (47%)	4 (10%)	13 (33%)	4 (10%)
FL180 - FL290	66 (67%)	5 (5%)	16 (16%)	12 (12%)
Above FL290	104 (58%)	7 (4%)	35 (20%)	33 (18%)

Table 4-20. Level Off downward sense RAs Duration – 12 seconds or longer.

RA duration	
Min [s]	12
Max [s]	316
Average [s]	29.4

4.4.5 Maintain Vertical Speed RA – duration of 12 seconds or longer

Only one Maintain Vertical Speed RA was 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.

4.5 Secondary RAs – duration of 12 seconds or longer

Out of 169 recorded secondary RAs, 129 (76.3%) 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 4-21. All types of secondary RAs – 12 seconds or longer.

Secondary RA – a 12-second duration or longer					
	Followed	Not followed - too weak	Opposite	Excessive	The total number of each RA type (100%=129)
Climb	0 (0%)	4 (80%)	1 (20%)	0 (0%)	5 (4%)
Reversal Climb	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1 (1%)
Increase Climb	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Descend/Crossing Descend	3 (37%)	5 (63%)	0 (0%)	0 (0%)	8 (6%)
Reversal Descend	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Level Off – upward sense	47 (75%)	2 (3%)	3 (5%)	11 (17%)	63 (48%)
Level Off – downward sense	33 (67%)	1 (2%)	2 (4%)	13 (27%)	49 (38%)
Maintain Vertical Speed	Not assessed				1 (1%)
Total	86 (67%)	13 (10%)	6 (4%)	24 (19%)	

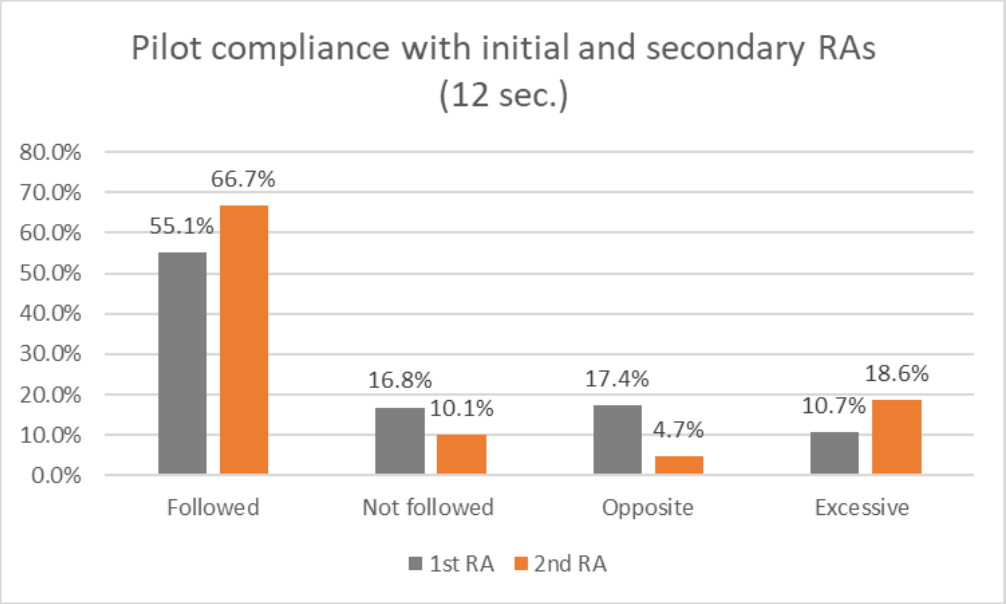

Figure 4-12. Pilot compliance with initial and secondary RAs – 12 seconds or longer.

4.6 Third and subsequent RAs – duration of 12 seconds or longer

Fifteen tertiary RAs lasted 12 seconds or more.

Table 4-22. 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	1	0	0	0	**1**
Descend	0	0	1	0	**1**
Reversal Descend	0	1	0	0	**1**
Level Off – upward sense	2	0	0	1	**3**
Level Off – downward sense	7	0	0	0	**7**
Monitor Vertical Speed	Not Assessed				**2**
Total	**10**	**1**	**1**	**1**	

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

4.7 Pilot compliance – duration of 16 seconds or longer

Out of 1176 recorded RAs, 813 (69%) 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 4-23. All types of first RAs – 16 seconds or longer.

First RA - an 16-second duration or longer					
	Followed	Not followed - too weak	Opposite	Excessive	The total number of each RA type (100%=813)
Climb	6 (14%)	20 (48%)	9 (21%)	7 (17%)	42 (5%)
Descend/Crossing Descend	9 (23%)	25 (64%)	2 (5%)	3 (8%)	39 (4%)
Level Off – upward sense	198 (70%)	12 (4%)	21 (7%)	51 (19%)	282 (35%)
Level Off – downward sense	199 (58%)	19 (5%)	47 (14%)	77 (23%)	342 (42%)
Maintain Vertical Speed	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1 (1%)
Monitor Vertical Speed	Not assessed				107 (13%)
Total	413 (58%)	76 (11%)	79 (11%)	138 (20%)	

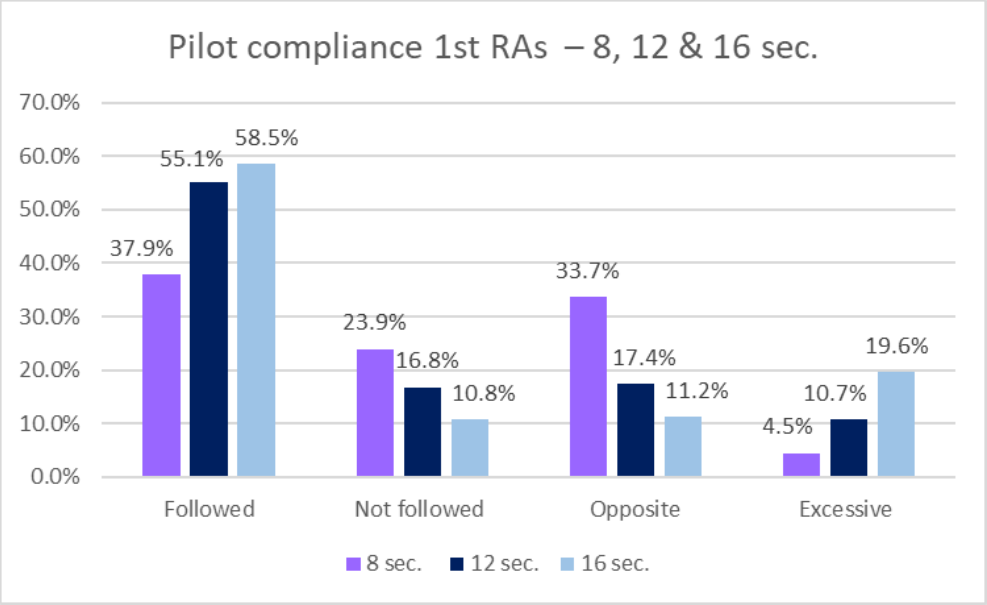

Figure 4-13. Pilot compliance with first RAs – comparison of the previous results.

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

4.7.1 Climb RAs – duration of 16 seconds or longer

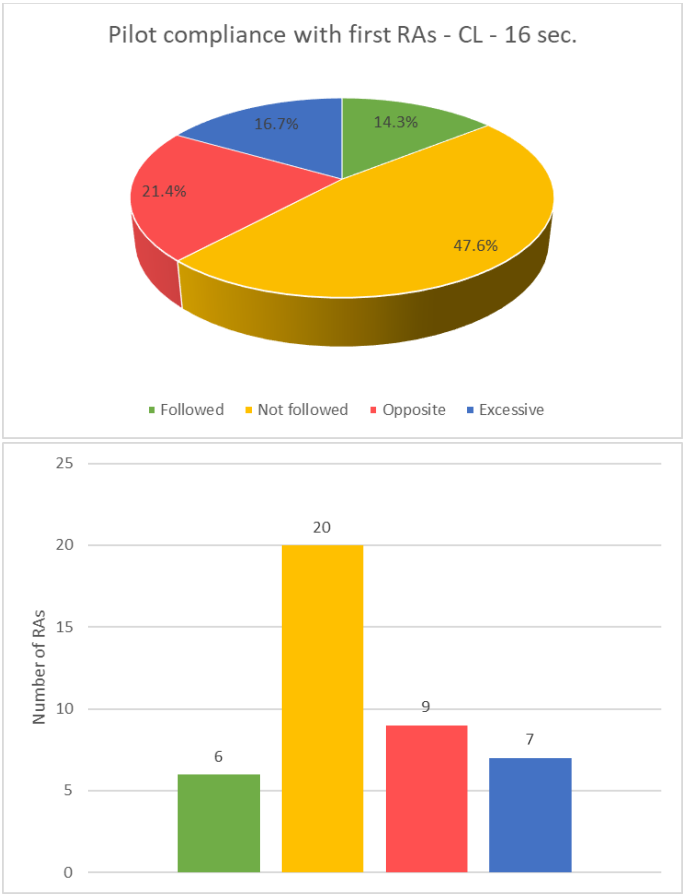

Figure 4-14. Pilot Compliance with first Climb RAs – 16 seconds or longer.

Table 4-24. Climb RAs – 16-second duration or longer, altitude bands.

Pilot compliance based on altitude – 42 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	0 (0%)	1 (25%)	3 (75%)	0 (0%)
FL30 - FL100	1 (5%)	11 (61%)	5 (28%)	1 (6%)
FL100 - FL180	2 (29%)	4 (57%)	0 (0%)	1 (14%)
FL180 - FL290	2 (23%)	3 (33%)	1 (11%)	3 (33%)
Above FL290	1 (25%)	1 (25%)	0 (0%)	2 (50%)

Table 4-25. Climb RAs duration – 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	84
Average [s]	21.2

4.7.2 Descend RAs – duration of 16 seconds or longer

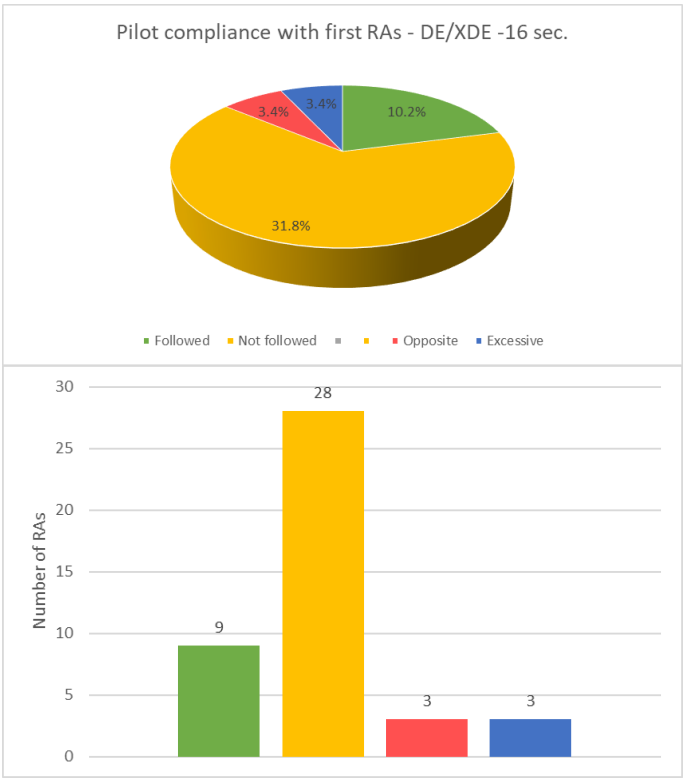

Figure 4-15. Pilot Compliance with first Descend/Crossing Descend RAs – 16 seconds or longer.

Table 4-26. Descend/Crossing Descend RAs – 16-second duration or longer, altitude bands

Pilot compliance based on altitude – 39 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	0 (0%)	5 (100%)	0 (0%)	0 (0%)
FL30 - FL100	3 (17%)	14 (78%)	1 (5%)	0 (0%)
FL100 - FL180	0 (0%)	2 (100%)	0 (0%)	0 (0%)
FL180 - FL290	0 (0%)	2 (50%)	0 (0%)	1 (25%)
Above FL290	5 (50%)	3 (30%)	0 (0%)	2 (20%)

Table 4-27. Descend/Crossing Descend RA duration – 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	100
Average [s]	25.9

4.7.3 Level off upward sense RAs – duration of 16 seconds or longer

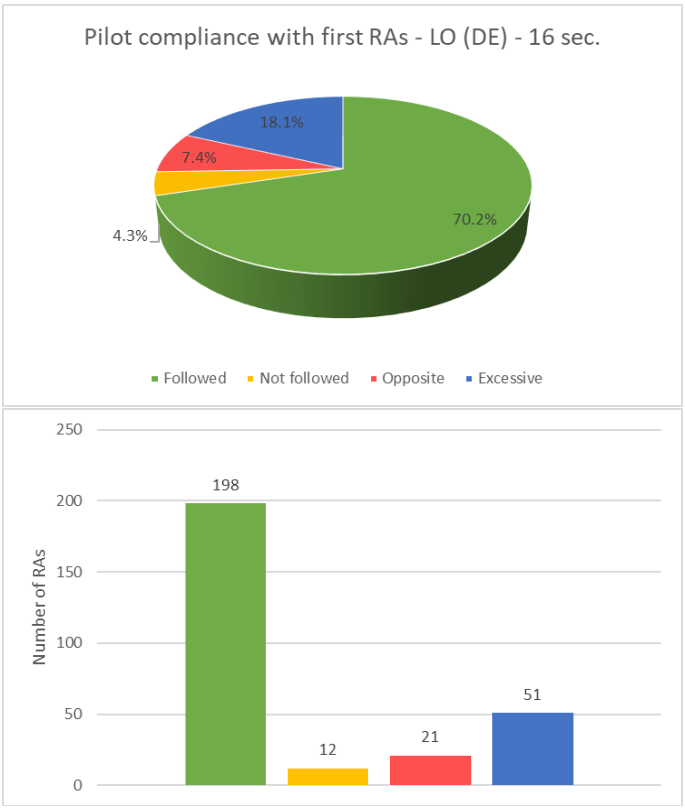

Figure 4-16. Pilot Compliance with first Level Off upward sense RAs – 16 seconds duration.

Table 4-28. Level Off upward 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 (60%)	1 (20%)	0 (0%)	1 (20%)
FL30 - FL100	21 (78%)	1 (4%)	2 (7%)	3 (11%)
FL100 - FL180	29 (80%)	1 (3%)	2 (6%)	4 (11%)
FL180 - FL290	55 (64%)	4 (5%)	8 (9%)	19 (22%)
Above FL290	90 (70%)	5 (4%)	9 (7%)	24 (19%)

Table 4-29. Level Off upward sense RAs duration – 16 seconds or longer.

RA duration	
Min [s]	16
Max [s]	204
Average [s]	33.5

4.7.4 Level off downward sense RAs – duration of 16 seconds or longer

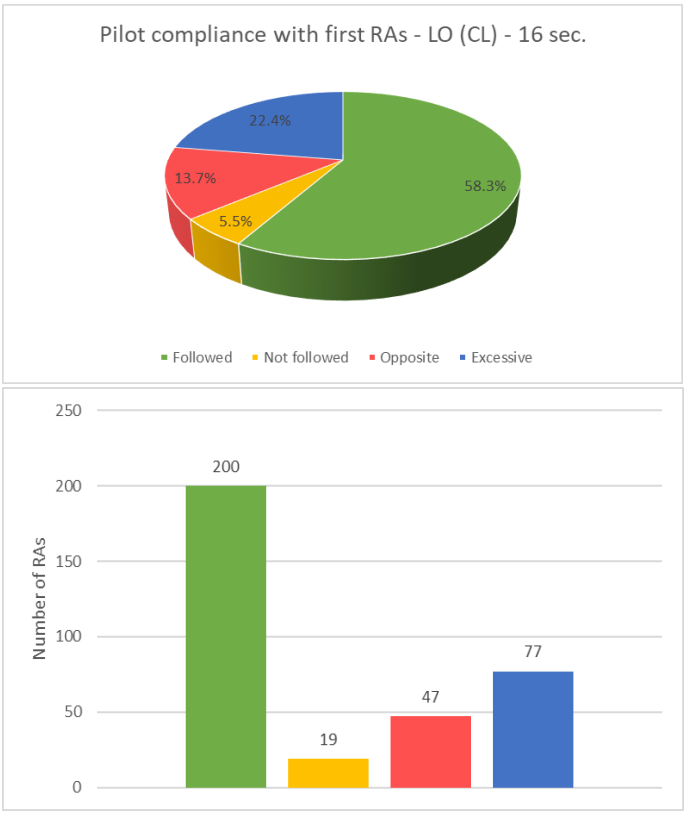

Figure 4-17. Pilot Compliance with first Level Off downward sense RAs –16 seconds or longer.

Table 4-30. Level Off downward sense RAs – 16-second duration or longer, flight levels.

Pilot compliance based on altitude – 342 registered RAs represent 100%				
	Followed	Not followed - too weak	Opposite	Excessive
Below FL30	0 (0%)	0 (0%)	0 (0%)	0 (0%)
FL30 - FL100	30 (57%)	8 (15%)	8 (15%)	7 (13%)
FL100 - FL180	17 (52%)	2 (6%)	8 (24%)	6 (18%)
FL180 - FL290	55 (59%)	4 (4%)	13 (14%)	21 (23%)
Above FL290	97 (60%)	5 (3%)	18 (11%)	43 (26%)

Table 4-31. Level Off downward sense RAs duration – 16 seconds duration or longer.

RA duration	
Min [s]	16
Max [s]	316
Average [s]	31.1

4.7.5 Maintain Vertical Speed RA – duration of 16 seconds or longer

Only 1 Maintain Vertical Speed RA was 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.

5 Assessment Results: *Method B*

Following the first issue of this document and the presentation of the pilot compliance results to various expert audiences, an alternative approach to assessing pilot compliance has been devised and is described in this chapter.

Note, this approach, referred to as *Method B* has only been applied to first RAs. Any subsequent RAs have not been analysed.

Method B addresses concerns raised over the ability of a pilot to respond promptly, for example, to a Climb RA whilst in descent. Under the previous scheme (*Method A,* see section 4), pilot compliance was judged at the 8 and 12 second mark after the RA without regard to the vertical rate at the time the RA was triggered, the time sufficient for a pilot response to be initiated and the expected limit on aircraft acceleration.

Method B takes all of these into consideration. It makes the following assumptions:

- The pilot has to process and respond to the RA and is allowed a time budget of 5 seconds to start the required manoeuvre (as per the standard pilot response, see ICAO Manual);
- The pilot is expected to maintain a vertical acceleration of 0.25*g*;
- The vertical rates provided in the radar recordings are subject to noise / altitude quantisation and tracker lag; therefore to take account of this imperfect data a vertical rate tolerance of ±300 ft/min is allowed for in the assessment of pilot compliance.

Compared to the previous method, the new scheme is able to give a pilot the credit of 'following the RA' if the change in vertical rate is sufficient (at +8 seconds and +12 seconds) even if the required final vertical rate has not yet been met.

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

- **Following**: the pilot's reaction is consistent with a manoeuvre towards the required vertical rate, with the anticipated acceleration and reaction time (including the required vertical rate being achieved);
- **Weak Response**: the pilot has made an adjustment in vertical speed in the required direction, but insufficient in vertical speed or acceleration to fulfil the requirement;
- **No Response**: any change in the vertical speed is within the measurement noise and therefore no response is registered;
- **Opposite**: the change in vertical speed performed by pilot is in the opposite vertical sense comparing to the instruction generated by TCAS;
- **Excessive**: the response exceeds the required vertical rate.

The detailed algorithms used to compute *Method B* pilot compliance are presented in Annex 1.

5.1 Pilot Compliance with Climb RAs

Pilot compliance with Climb RAs at 8 seconds and at 12 seconds is presented in Table 5-1 below.

Table 5-1. Climb RAs – pilot compliance matrix at 8 seconds and 12 seconds.

			Climb RA: Compliance at 8 seconds				
			Following	**Weak Response**	**No Response**	**Opposite**	**Excessive**
			44	61	35	4	4
12 seconds	**RA over (COC)**	57	16	24	13	2	2
	Following	19	15	3	0	0	1
	Weak Response	38	5	33	0	0	0
	No Response	22	1	1	20	0	0
	Opposite	5	1	0	2	2	0
	Excessive	7	6	0	0	0	1

The compliance is shown at 8 seconds in the first row of numbers, and the compliance at 12 seconds is shown in the first column of numbers. At 8 seconds after the RA, 44 (29.7%) pilots are considered to be following the RA. At 12 seconds after the RA 19 (20.9%) pilots are following the RA, although it is worth noting that the RA is over – i.e. Clear of Conflict (COC) conditions exist – for 57 (38.5%) of the events, and so these are not included in the compliance assessment at 12 seconds.

The total number of ongoing Climb RAs at 8 seconds is 148. The total number of ongoing Climb RAs at 12 seconds is 91.

The remaining rows and columns in the table provide a matrix of values that show how the RA compliance evolves between 8 seconds and 12 seconds. For instance, of the 35 pilots who were not responding at all to the RA at 8 seconds, at 12 seconds 20 of them were still not responding, 2 were now undertaking a manoeuvre ‘opposite’ to that required, and 13 were not assessed as the RA had terminated. The vast majority of pilots (78.0%) seem to stick with the original reaction whether that be following the RA as required, following it weakly, or not responding at all.

The compliance rates for Climb RAs (percentages in brackets) at 8 seconds and 12 seconds are shown in Table 5-2 and illustrated in Figure 5-1.

Table 5-2. Climb RAs – pilot compliance rates.

	Following	Weak Response	No Response	Opposite	Excessive
Compliance at 8 seconds	44 (29%)	61 (41%)	35 (24%)	4 (3%)	4 (3%)
Compliance at 12 seconds	19 (21%)	38 (42%)	22 (24%)	5 (5%)	7 (8%)

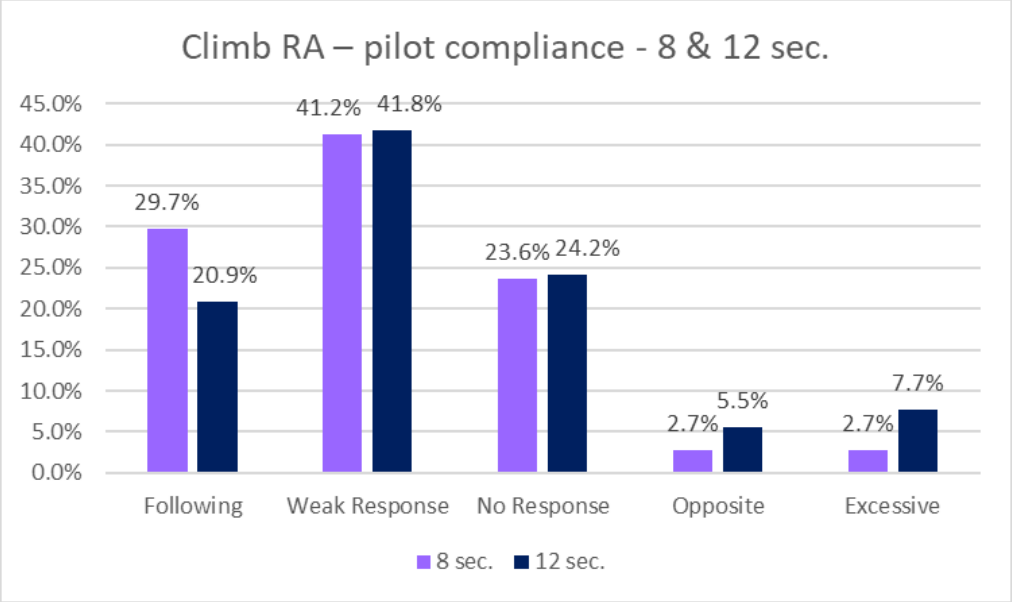

Figure 5-1. Climb RAs – pilot compliance rates at 8 and 12 sec. after the RA.

5.2 Compliance with Descend RAs

Pilot compliance with Descend RAs at 8 seconds and at 12 seconds is presented in Table 5-3 below.

The total number of ongoing Descend RAs at 8 seconds is 122. The total number of ongoing Descend RAs at 12 seconds is 88.

The compliance rates for Climb and Descent RAs appear to be similar. Compared to *Method A*, *Method B* has far fewer 'opposite' responses to the RA. This is because *Method B* requires the aircraft to have changed vertical rate since the RA was triggered in the opposite sense to the RA in order to be indicated as 'opposite'.

The vast majority of pilots (78.4%) seem to stick with the original response (or non-response), whether that be following the RA as required, following it weakly, excessively or in the opposite direction to that required.

Table 5-3. Descend RAs – pilot compliance matrix at 8 seconds and 12 seconds.

			Descend RA: Compliance at 8 seconds				
			Following	Weak Response	No Response	Opposite	Excessive
			41	43	28	5	5
12 seconds	RA over (COC)	34	6	14	9	2	3
	Following	27	24	3	0	0	0
	Weak Response	33	8	24	1	0	0
	No Response	20	2	2	16	0	0
	Opposite	5	0	0	2	3	0
	Excessive	3	1	0	0	0	2

The compliance rates for Descend RAs (percentages in brackets) at 8 seconds and 12 seconds are shown in Table 5-4 and illustrated in Figure 5-2.

Table 5-4. Descend RAs – pilot compliance rates.

	Following	Weak Response	No Response	Opposite	Excessive
Compliance at 8 seconds	41 (34%)	43 (35%)	28 (23%)	5 (4%)	5 (4%)
Compliance at 12 seconds	27 (31%)	33 (37%)	20 (23%)	5 (6%)	3 (3%)

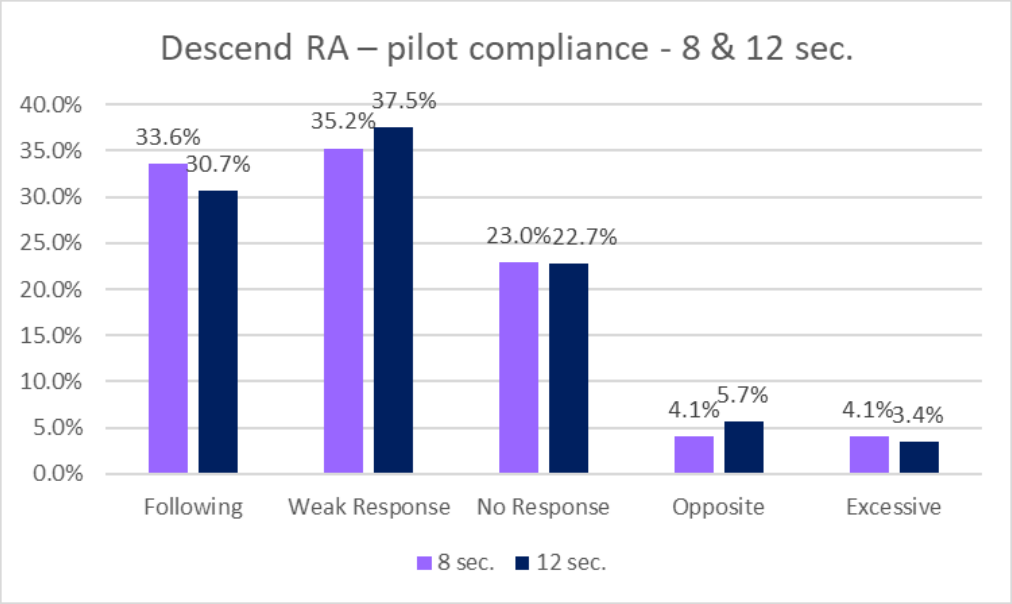

Figure 5-2. Descend RAs – pilot compliance rates at 8 and 12 sec. after the RA.

5.3 Compliance with Level Off RAs (upward sense)

Pilot compliance with Level Off RAs (upward sense) at 8 seconds and at 12 seconds is presented in Table 5-5 below.

The total number of ongoing Level Off (upward sense) RAs at 8 seconds and at 12 seconds is 282.

Pilot compliance to Level Off RAs is much better than for Climb or Descent RAs for Level Off (upward sense) RAs the compliance rate is 68.8% (at RA + 8 seconds) and for Level Off (downward sense) RAs the compliance rate is 62.3%. A significant proportion of pilots follow the sense of the RA, but respond weakly. For Level Off (upward sense) RAs this is 23.4% and for Level Off (downward sense) RAs this is 32.5%.

For Level Off (upward sense) RAs, the vast majority of pilots that start by following the RA seem to stick with the original response (154: 79.4%), although a few (24:12.4%) weaken their response 4 seconds later. The majority of pilots (35: 53.0%) who started with a weak response strengthened their response to ‘following’ at the 12 second sample point. Of the 8 pilots who were not responding at the 8 seconds marker, four seconds later four had a weak response to the RA and 1 was ‘following’. It may be that these changes in compliance reflect a commonly held view that pilots are often in the practice of delaying their response to a Level Off RA until they are at an ATC Flight Level.

Table 5-5. Level Off RAs (upward sense) – pilot compliance matrix at 8 seconds and 12 seconds.

			Level Off (upward) RA: Compliance at 8 seconds				
			Following	Weak Response	No Response	Opposite	Excessive
			194	66	8	0	14
12 seconds	Following	191	154	35	1	0	1
	Weak Response	58	24	30	4	0	0
	No Response	4	0	1	3	0	0
	Opposite	0	0	0	0	0	0
	Excessive	29	16	0	0	0	13

The compliance rates for upward sense Level Off RAs (percentages in brackets) at 8 seconds and 12 seconds are shown in Table 5-6 and illustrated in Figure 5-3.

Table 5-6. Level Off RAs (upward sense) – pilot compliance rates.

	Following	Weak Response	No Response	Opposite	Excessive
Compliance at 8 seconds	194 (69%)	66 (23%)	8 (3%)	0 (0%)	14 (5%)
Compliance at 12 seconds	191 (68%)	58 (20%)	4 (2%)	0 (0%)	29 (10%)

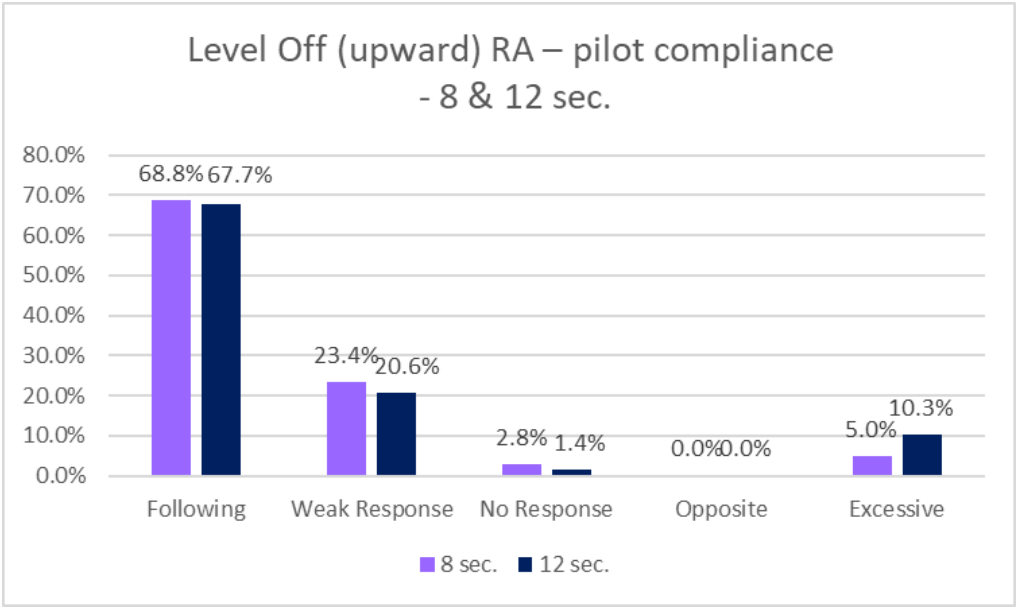

Figure 5-3. Level Off (upward sense) RAs – pilot compliance rates at 8 and 12 sec. after the RA.

5.4 Compliance with Level Off RAs (downward sense)

Pilot compliance with Level Off RAs (downward sense) at 8 seconds and at 12 seconds is presented in Table 5-7 below.

The total number of ongoing Level Off (downward sense) RAs at 8 seconds and at 12 seconds is 342.

The vast majority of pilots (67.3%) seem to stick with the original response (or non-response), whether that be following the RA as required, or following it weakly.

Table 5-7. Level Off RAs (downward sense) – pilot compliance matrix at 8 seconds and 12 seconds.

			Compliance at 8 seconds				
			Following	**Weak Response**	**No Response**	**Opposite**	**Excessive**
			213	111	6	0	12
12 seconds	**Following**	194	150	43	1	0	0
	Weak Response	99	26	68	5	0	0
	No Response	0	0	0	0	0	0
	Opposite	0	0	0	0	0	0
	Excessive	49	37	0	0	0	12

The compliance rates for downward sense Level Off RAs (percentages in brackets) at 8 seconds and 12 seconds are shown in Table 5-8 and illustrated in Figure 5-4.

Table 5-8. Level Off RAs (downward sense) – pilot compliance rates.

	Following	**Weak Response**	**No Response**	**Opposite**	**Excessive**
Compliance at 8 seconds	213 (62%)	111 (32%)	6 (2%)	0 (0%)	12 (4%)
Compliance at 12 seconds	194 (57%)	99 (29%)	0 (0%)	0 (0%)	49 (14%)

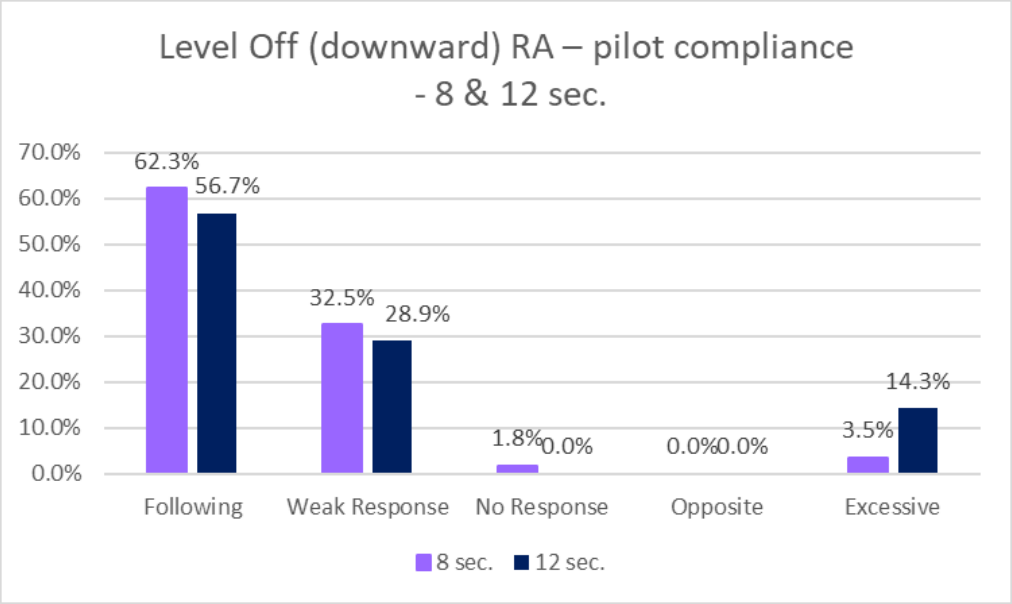

Figure 5-4. Level Off (downward sense) RAs – pilot compliance rates at 8 and 12 sec. after the RA.

5.5 RA Compliance Rates by Vertical Rate (Attitude) at the Time of RA

The pilot compliance was further assessed using *Method B* to determine if there are any differences in the compliance rates depending on aircraft's vertical rate (attitude) at the time of RA.

The vertical attitude was assigned as follows:

- **Climb –** rates > 100 ft/min.
- **Level –** rates of 0 ft/min. ±100 ft/min.
- **Descend –** rates < –100 ft/min.

Table 5-9 shows the pilot compliance statistics broken out by the vertical attitude.

For Climb and Descend RAs the compliance rate appears to be better when the RA is in the same vertical direction as the vertical attitude of the aircraft RA. For Level Off RAs, there is no clear trend in pilot compliance versus vertical attitude. The vast majority of RAs fall into a single category ('descending' for the Level Off upwards RA, 'climbing' for the Level off downwards RA), leaving the other categories in each table sparsely populated.

Table 5-9. RA Compliance Rates by Vertical Rate (Attitude) at the Time of RA.

RA	Attitude	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb (n=148)	**Climbing**	29 (40%)	26 (36%)	12 (16%)	2 (3%)	4 (5%)	73
	Level	2 (9%)	4 (18%)	15 (68%)	1 (5%)	0	22
	Descending	13 (25%)	31 (58%)	8 (15%)	1 (2%)	0	53
Descend (n=122)	**Climbing**	12 (43%)	13 (46%)	1 (4%)	2 (7%)	0	28
	Level	0	7 (44%)	9 (56%)	0	0	16
	Descending	29 (37%)	23 (29%)	18 (23%)	3 (4%)	5 (6%)	78
Level Off (upward) (n=353)	**Climbing**	1 (25%)	0	0	0	3 (75%)	4
	Level	9 (75%)	0	0	0	3 (25%)	12
	Descending	218 (65%)	83 (25%)	19 (6%)	1 (0%)	16 (5%)	337
Level Off (downward) (n=406)	**Climbing**	245 (61%)	131 (33%)	12 (3%)	0	11 (3%)	399
	Level	3 (50%)		0	0	3 (50%)	6
	Descending	0	0	0	0	1 (100%)	1

5.6 Overall RA Compliance Rates

The mean compliance rates (percentages in brackets) for all the above RAs (Climbs, Descends and Level Offs) at 8 seconds and 12 seconds are shown in Table 5-9 and illustrated in Figure 5-5.

Table 5-10. Overall pilot compliance rates.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Compliance at 8 seconds	492 (55%)	281 (31%)	77 (9%)	9 (1%)	35 (4%)	894
Compliance at 12 seconds	431 (54%)	228 (28%)	46 (6%)	10 (1%)	88 (11%)	803

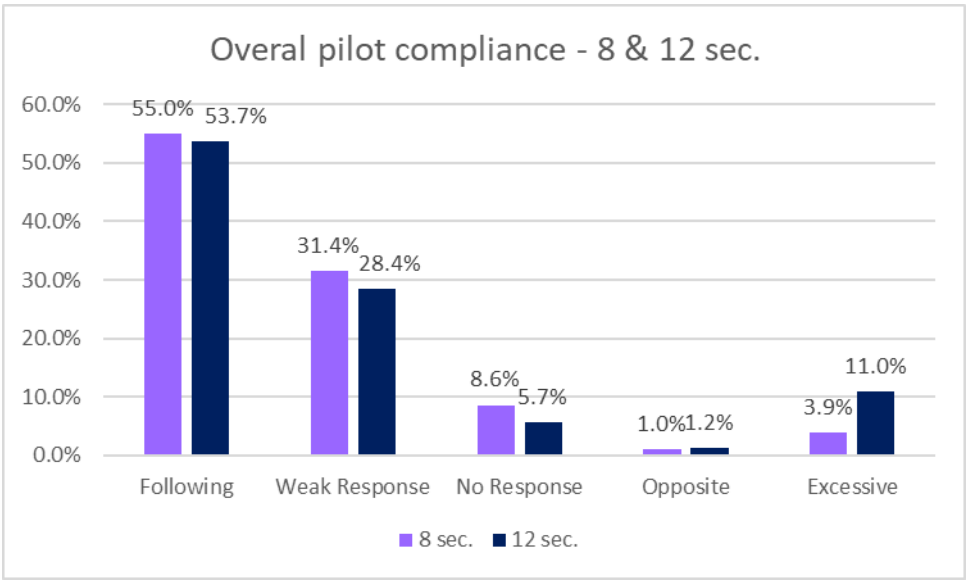

Figure 5-5. Overall pilot compliance rates at 8 and 12 sec. after the RA.

6 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 greater the VMD, the better level of safety is achieved.

In the previous sections, the focus was on the validation of pilot behaviour using two methods to assess compliance, *Method A* and *Method B*. Both methods are based on IATA/EUROCONTROL Guidance Material, although *Method A* follows the recommendation most strictly. These analyses are very narrow and do 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[13], but to provide an overall insight into how safety, from the TCAS point of view, might be affected depending on pilot compliance with Resolution Advisories.

6.1 Pre-conditions

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.

The following conditions have been used to down-select the encounters for VMD analysis:

- Aircraft, which received more than one RA will not be taken into 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).

The achieved VMD results are presented firstly using the *Method A* compliance scheme and secondly using the *Method B* compliance scheme.

The Reader's attention is drawn to the fact that relatively small numbers of cases may not provide fully representative results.

[13] A full safety assessment of the efficacy of TCAS RAs and the effect of pilot compliance requires a knowledge of the VMD both in practice and an estimate of the VMD in the absence of TCAS and is beyond the scope of this report.

6.2 Results – *Method A*

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

6.2.1 Vertical Miss Distances for Climb and Descend RAs

Table 6-1. VMD – Climb RA.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Followed	643	643	643	1
Not followed	331	24	858	11
Opposite	268	87	875	8

Table 6-2. VMD – Descend RAs.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Followed	407	327	548	4
Not followed	295	50	646	12
Opposite	60	50	69	2

The correlation between the quality of compliance and vertical miss distances is clear. A 643- 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.

6.2.2 Vertical Miss Distances for Level Off RAs

Table 6-3. VMD – Level Off upward sense.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Followed	688	418	994	17
Not followed	565	454	705	3
Opposite	637	271	988	13

Table 6-4. VMD – Level Off downward sense.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Followed	615	369	974	6
Not followed	836	512	999	3
Opposite	872	639	998	7

There is no significant difference between the VMD values shown in Table 6-3, unlike the case for the values presented in Table 6-1 and Table 6-2. 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 ft 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 6-4 are susceptible to misinterpretation. As shown in 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 6-5).

Table 6-5. The percentage of opposite RA responses – downwards sense.

8-second threshold	12-second threshold	16-second threshold
42.3%	22.3%	13.7%

Most likely, the reason why there is sometimes a delay in pilot response 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.

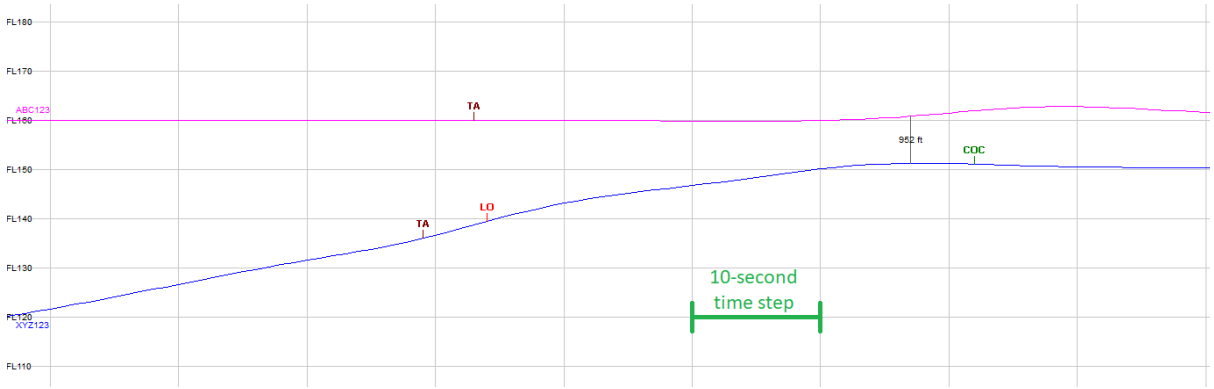

Figure 6-1. An example of a not followed RA (#1).

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 an inappropriate compliance, but these scenarios are rather infrequent events and their VMDs are much smaller.

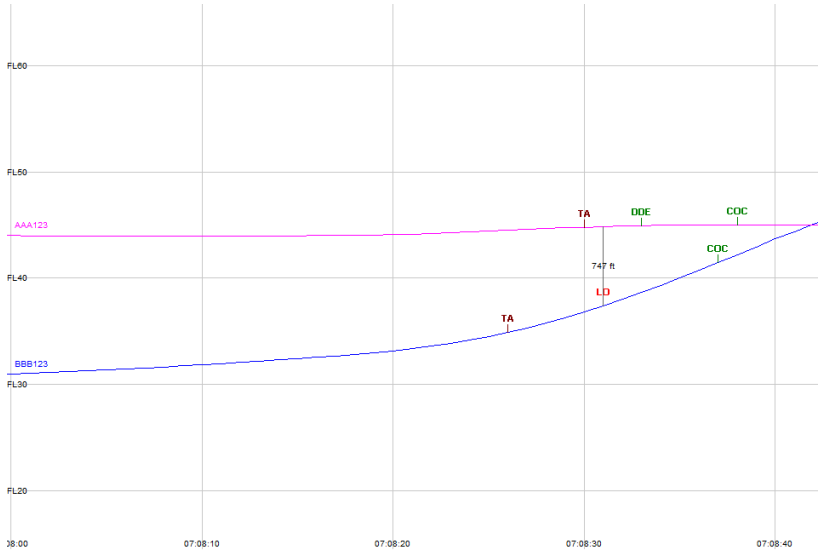

Figure 6-2. An example of a not followed RA (#2).

6.3 Results – *Method B*

The VMD results in this section are derived by assessing the pilot compliance using *Method B*. The classification then leads to a mean VMD for each pilot compliance category.

In tables below, each row represents the average value of VMD for following, weak response, no response and opposite categories.

6.3.1 Vertical Miss Distances for Climb and Descend RAs

Table 6-6. VMD – Climb RAs.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Following	625	606	643	2
Weak Response	-	-	-	0
No Response	297	24	875	17
Opposite	129	129	129	1

Table 6-7. VMD – Descend RAs.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Following	393	327	548	5
Weak Response	336	76	606	3
No Response	250	50	646	9
Opposite	69	69	69	1

Despite the relatively small sample sizes, the same correlation between the quality of compliance and vertical miss distances is apparent using *Method B* for the pilot compliance computation. On average, the greatest vertical separation is achieved when the pilot follows the RA as required. There are no weak response Climb RA encounters that fulfil the preconditions for assessment. However, weak response Descend RAs do seem to result in a vertical separation which falls (on average) between the following and no response categories. An opposite response results in the smallest vertical separation between the aircraft, and therefore a significantly higher risk of collision exists in these cases.

6.3.2 Vertical Miss Distances for Level Off RAs

Table 6-8. VMD – Level Off upward sense.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Following	688	418	996	17
Weak Response	767	490	988	7
No Response	512	271	814	9
Opposite	-	-	-	0

Table 6-9. VMD – Level Off, downward sense.

Category	Mean VMD [ft]	Minimum VMD [ft]	Maximum VMD [ft]	Number of Samples
Following	667	375	977	7
Weak Response	855	512	99	8
No Response	792	792	792	1
Opposite	-	-	-	0

As described in section 6.2.2, caution should be taken in assessing the VMD results for Level Off RAs since CPA can occur quite some time after the RA. The recorded VMD can therefore be independent of the RA and the pilot response.

7 Pilot Compliance by Categories

Since the first version of this document was published, interest has arisen around the pilot compliance rate for various categories of aircraft and operation.

In order to address these questions, pilot compliance is presented in this section according to the following:

- EASA / non-EASA State registered aircraft[14]
- Type of operation (airline, business, cargo or military and other operations)
- Aircraft type group (including Airbus families, Boeing families, Embraer regional jets, etc.)

Pilot compliance is shown as a series of tables, using both *Method A* and *Method B* compliance algorithms, using the vertical rate 8 seconds after the RA. The number of aircraft in each compliance category is indicated as well as the percentage.

7.1 Pilot Compliance by EASA / non-EASA Registration

Pilot compliance is presented for EASA and non-EASA registered aircraft using both *Method A* and *Method B* in Table 7-1, Table 7-2, Table 7-3 and Table 7-4, below:

[14] The State of registration was determined based on the Mode S 24-bit address. At the time when the RA data was collected, the following were EASA States (alphabetically): Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, and United Kingdom.

Table 7-1. Pilot Compliance (*Method A*) – EASA Registered Aircraft.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	31 (23%)	79 (58%)	22 (16%)	4 (3%)	136
Descend	26 (24%)	69 (64%)	7 (7%)	5 (5%)	107
Level Off (upward)	122 (42%)	35 (12%)	115 (40%)	19 (6%)	291
Level Off (downward)	150 (47%)	35 (11%)	121 (38%)	11 (4%)	317
Total	329 (39%)	218 (26%)	26 (31%)	39 (4%)	851

Table 7-2. Pilot Compliance (*Method B*) – EASA Registered Aircraft.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	41 (30%)	53 (39%)	34 (25%)	4 (3%)	4 (3%)	136
Descend	34 (32%)	40 (37%)	23 (21%)	5 (5%)	5 (5%)	107
Level Off (upward)	188 (65%)	68 (23%)	15 (5%)	1 (1%)	19 (6%)	291
Level Off (downward)	205 (65%)	93 (29%)	8 (2%)	0 (0%)	11 (4%)	317
Total	468 (55%)	254 (30%)	80 (10%)	10 (1%)	39 (4%)	851

Table 7-3. Pilot Compliance (*Method A*) – Non-EASA Registered Aircraft.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	2 (17%)	6 (50%)	4 (33%)	0 (0%)	12
Descend	5 (33%)	10 (67%)	0 (0%)	0 (0%)	15
Level Off (upward)	25 (40%)	6 (10%)	28 (45%)	3 (5%)	62
Level Off (downward)	27 (30%)	7 (8%)	51 (57%)	4 (5%)	89
Total	59 (33%)	29 (16%)	83 (47%)	7 (4%)	178

Table 7-4. Pilot Compliance (*Method B*) – Non-EASA Registered Aircraft.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	3 (25%)	8 (67%)	1 (8%)	0 (0%)	0 (0%)	12
Descend	7 (47%)	3 (20%)	5 (33%)	0 (0%)	0 (0%)	15
Level Off (upward)	40 (65%)	15 (24%)	4 (6%)	0 (0%)	3 (5%)	62
Level Off (downward)	43 (47%)	38 (43%)	4 (5%)	0 (0%)	4 (5%)	89
Total	93 (52%)	64 (36%)	14 (8%)	0 (0%)	7 (4%)	178

From the results presented, it is not entirely clear whether crews of EASA registered performance is significantly different comparing to crews of non-EASA registered aircraft. According to *Method A*, pilot compliance is slightly better for EASA registered aircraft (38.9% versus 33.1%). This also holds true for *Method B* (55.0% versus 52.2%). However, the difference is small, and possibly within the margin of error given imperfection of the input data. Furthermore, when 'weak response' is included, then non-EASA registered aircraft follow the RA either fully or weakly 88.2% of the time, as a opposed to EASA registered aircraft which follow the RA either fully or weakly 84.8% of the time.

7.2 Pilot Compliance by Type of Operation

Type of operation is broken out according to the following categories:

- Airline;
- Business;
- Cargo operators;
- Military and other operations.

The results are presented for pilot compliance by *Method A* and *Method B* in Table 7-5 through Table 7-12.

Table 7-5. Pilot Compliance (*Method A*) – Airlines.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	27 (27%)	61 (60%)	9 (9%)	4 (4%)	101
Descend	20 (23%)	57 (67%)	4 (5%)	4 (5%)	85
Level Off (upward)	121 (43%)	37 (13%)	111 (39%)	15 (5%)	284
Level Off (downward)	144 (49%)	34 (12%)	104 (35%)	11 (4%)	293
Total	312 (41%)	189 (25%)	228 (30%)	34 (4%)	763

Table 7-6. Pilot Compliance (Method B) – Airlines.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	36 (36%)	47 (46%)	13 (13%)	1 (1%)	4 (4%)	101
Descend	28 (33%)	34 (40%)	15 (17%)	4 (5%)	4 (5%)	85
Level Off (upward)	192 (69%)	64 (22%)	13 (4%)	0 (0%)	15 (5%)	284
Level Off (downward)	194 (66%)	80 (27%)	8 (3%)	0 (0%)	11 (4%)	293
Total	450 (59%)	225 (30%)	49 (6%)	5 (1%)	34 (4%)	763

Table 7-7. Pilot Compliance (*Method A*) – Business Aircraft.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	5 (16%)	17 (53%)	10 (31%)	0 (0%)	32
Descend	6 (25%)	14 (58%)	3 (13%)	1 (4%)	24
Level Off (upward)	21 (42%)	4 (8%)	20 (40%)	5 (10%)	50
Level Off (downward)	17 (22%)	5 (6%)	56 (71%)	1 (1%)	79
Total	49 (26%)	40 (22%)	89 (48%)	7 (4%)	185

Table 7-8. Pilot Compliance (*Method B*) – Business Aircraft.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	7 (22%)	12 (37%)	12 (37%)	1 (4%)	0 (0%)	32
Descend	7 (30%)	6 (25%)	9 (37%)	1 (4%)	1 (4%)	24
Level Off (upward)	27 (54%)	12 (24%)	5 (10%)	1 (2%)	5 (10%)	50
Level Off (downward)	33 (42%)	41 (52%)	4 (5%)	0 (0%)	1 (1%)	79
Total	74 (40%)	71 (38%)	30 (16%)	3 (2%)	7 (4%)	185

Table 7-9. Pilot Compliance (*Method A*) – Cargo Operators.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	3 (100%)	0 (0%)	0 (0%)	3
Descend	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1
Level Off (upward)	2 (25%)	0 (0%)	5 (63%)	1 (12%)	8
Level Off (downward)	10 (43%)	2 (9%)	9 (39%)	2 (9%)	23
Total	12 (34%)	6 (17%)	14 (40%)	3 (9%)	35

Table 7-10. Pilot Compliance (*Method B*) – Cargo Operators.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	2 (67%)	1 (33%)	0 (0%)	0 (0%)	3
Descend	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1
Level Off (upward)	5 (63%)	2 (25%)	0 (0%)	0 (0%)	1 (12%)	8
Level Off (downward)	13 (56%)	8 (35%)	0 (0%)	0 (0%)	2 (9%)	23
Total	18 (51%)	13 (37%)	1 (3%)	0 (0%)	3 (9%)	35

Table 7-11. Pilot Compliance (*Method A*) – Military and other operations.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	1 (8%)	4 (33%)	7 (59%)	0 (0%)	12
Descend	5 (42%)	7 (58%)	0 (0%)	0 (0%)	12
Level Off (upward)	3 (27%)	0 (0%)	7 (64%)	1 (9%)	11
Level Off (downward)	6 (56%)	1 (9%)	3 (27%)	1 (9%)	11
Total	15 (33%)	12 (26%)	17 (37%)	2 (4%)	46

Table 7-12. Pilot Compliance (Method B) – Military and other operations.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	1 (8%)	0 (0%)	9 (75%)	2 (17%)	0 (0%)	12
Descend	6 (50%)	2 (17%)	4 (33%)	0 (0%)	0 (0%)	12
Level Off (upward)	4 (36%)	5 (46%)	1 (9%)	0 (0%)	1 (9%)	11
Level Off (downward)	8 (73%)	2 (18%)	0 (0%)	0 (0%)	1 (9%)	11
Total	19 (41%)	9 (19%)	14 (30.4%)	2 (5%)	2 (5%)	46

As far as pilot compliance is concerned, commercial airline operations appear to perform better than the other categories of aircraft. The compliance rate (*Method A*: 'followed') for commercial aircraft is 40.9%, as opposed to 34.3% for cargo operators aircraft, 32.6% for military operations and 26.5% for business.

The same holds true for *Method B*. In this case, 59% of commercial airline aircraft follow the RA fully, and 29.5% weakly (88.5% in the combined 'fully' and 'weakly' group). 51.4% of cargo operators aircraft follow the RA fully and 37.1% weakly (88.5% in the combined group). 41.3% of 'military and other operations' aircraft follow the RA fully and 19.6% weakly (60.9% combined). 40% of business operations aircraft follow the RA fully and 38.4% weakly (78.4% combined).

7.3 Pilot Compliance by Aircraft Type Family / Group

In this section, pilot compliance (separately for *Method A* and *Method B*) for 13 most commonly observed aircraft type families / groups is presented. Table 7-13 lists the types taken into account (in the descending order by number of RA recorded for each type). The occurrences for the remaining aircraft types were too infrequent to be analysed.

Table 7-13. Aircraft type families / groups.

Aircraft type families / groups	**Number**
Airbus 320 Family (A318, A319, A320, A321)	272
Boeing 737-800/900	126
Embraer Regional Jets (E135, E145, E170, E190, E195)	117
Boeing 737-600/700	71
Cessna Business Jets (C56X, C25B, C25C, C525, etc.)	57
Falcon Business Jets (F2TH, F900, FA7X, FA20, FA50)	38
Bombardier Regional Jets (CRJ9, CRJX , CRJ7, CRJ2, etc.)	29
Boeing 737-300/400/500	28
Boeing 757 and Boeing 767 (all series)	26
Boeing 777 (all series)	24
Airbus A330 & A340 (all series)	21
Dash 8 (all variants)	16
Beechcraft Turboprops (B350, BE90, etc.)	14

7.3.1 Airbus A320 Family (A318, A319, A320, A321)

Table 7-14. Pilot Compliance (*Method A*) – Airbus A320 Family (A318, A319, A320, A321).

	Followed	Not Followed	Opposite	Excessive	Total
Climb	8 (18%)	30 (70%)	2 (5%)	3 (7%)	43
Descend	9 (27%)	23 (70%)	0 (0%)	1 (3%)	33
Level Off (upward)	51 (42%)	17 (14%)	50 (42%)	2 (2%)	120
Level Off (downward)	29 (38%)	12 (16%)	34 (45%)	1 (1%)	76
Total	97 (36%)	82 (30%)	86 (32%)	7 (2%)	272

Table 7-15. Pilot Compliance (*Method B*) – Airbus A320 Family (A318, A319, A320, A321).

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	12 (28%)	24 (56%)	4 (9%)	0 (0%)	3 (7%)	43
Descend	10 (31%)	14 (42%)	7 (21%)	1 (3%)	1 (3%)	33
Level Off (upward)	90 (75%)	28 (23%)	0 (0%)	0 (0%)	2 (2%)	120
Level Off (downward)	53 (70%)	19 (25%)	3 (4%)	0 (0%)	1 (1%)	76
Total	165 (61%)	85 (31%)	14 (5%)	1 (1%)	7 (2%)	272

7.3.2 Boeing 737-800/900

Table 7-16. Pilot Compliance (*Method A*) – Boeing 737-800/900.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	4 (22%)	13 (72%)	1 (6%)	0 (0%)	18
Descend	3 (14%)	16 (76%)	0 (0%)	2 (10%)	21
Level Off (upward)	17 (34%)	5 (10%)	25 (50%)	3 (6%)	50
Level Off (downward)	18 (49%)	9 (24%)	10 (27%)	0 (0%)	37
Total	42 (33%)	43 (34%)	36 (29%)	5 (4%)	126

Table 7-17. Pilot Compliance (*Method B*) – Boeing 737-800/900.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	7 (39%)	9 (50%)	2 (11%)	0 (0%)	0 (0%)	18
Descend	7 (33%)	9 (43%)	3 (14%)	0 (0%)	2 (10%)	21
Level Off (upward)	31 (62%)	10 (20%)	6 (12%)	0 (0%)	3 (6%)	50
Level Off (downward)	23 (62%)	12 (32%)	2 (6%)	0 (0%)	0 (0%)	37
Total	68 (54%)	40 (32%)	13 (10%)	0 (0%)	5 (4%)	126

7.3.3 Embraer Regional Jets

Table 7-18. Pilot Compliance (*Method A*) – Embraer Regional Jets.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	3 (75%)	1 (25%)	0 (0%)	4
Descend	5 (42%)	5 (42%)	1 (8%)	1 (8%)	12
Level Off (upward)	24 (70%)	3 (9%)	4 (12%)	3 (9%)	34
Level Off (downward)	43 (64%)	3 (4%)	14 (21%)	7 (11%)	67
Total	72 (61%)	14 (12%)	20 (17%)	11 (10%)	117

Table 7-19. Pilot Compliance (*Method B*) – Embraer Regional Jets.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	2 (50%)	1 (25%)	1 (25%)	0 (0%)	4
Descend	7 (59%)	3 (25%)	0 (0%)	1 (8%)	1 (8%)	12
Level Off (upward)	25 (73%)	5 (15%)	1 (3%)	0 (0%)	3 (9%)	34
Level Off (downward)	52 (78%)	7 (10%)	1 (1%)	0 (0%)	7 (11%)	67
Total	84 (72%)	17 (14%)	3 (3%)	2 (3%)	11 (9%)	117

7.3.4 Boeing 737-600/700

Table 7-20. Pilot Compliance (*Method A*) – Boeing 737-600/700.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	1 (33%)	2 (67%)	0 (0%)	0 (0%)	3
Descend	1 (33%)	2 (67%)	0 (0%)	0 (0%)	3
Level Off (upward)	5 (30%)	5 (30%)	6 (35%)	1 (5%)	17
Level Off (downward)	25 (52%)	3 (6%)	19 (40%)	1 (2%)	48
Total	32 (45%)	12 (17%)	25 (35%)	2 (3%)	71

Table 7-21. Pilot Compliance (*Method B*) – Boeing 737-600/700.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	2 (67%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	3
Descend	2 (67%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	3
Level Off (upward)	10 (59%)	6 (35%)	0 (0%)	0 (0%)	1 (6%)	17
Level Off (downward)	32 (67%)	15 (31%)	0 (0%)	0 (0%)	1 (2%)	48
Total	46 (65%)	22 (31%)	1 (1%)	0 (0%)	2 (3%)	71

7.3.5 Cessna Business Jets

Table 7-22. Pilot Compliance (*Method A*) – Cessna Business Jets.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	3 (23%)	3 (23%)	7 (54%)	0 (0%)	13
Descend	3 (38%)	4 (50%)	1 (12%)	0 (0%)	8
Level Off (upward)	4 (17%)	1 (4%)	13 (57%)	5 (22%)	23
Level Off (downward)	1 (8%)	2 (15%)	10 (77%)	0 (0%)	13
Total	11 (19%)	10 (18%)	31 (54%)	5 (9%)	57

Table 7-23. Pilot Compliance (*Method B*) – Cessna Business Jets.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	4 (31%)	2 (15%)	6 (46%)	1 (8%)	0 (0%)	13
Descend	3 (38%)	2 (25%)	2 (25%)	1 (12%)	0 (0%)	8
Level Off (upward)	8 (35%)	4 (17%)	5 (22%)	1 (4%)	5 (22%)	23
Level Off (downward)	2 (15%)	11 (85%)	0 (0%)	0 (0%)	0 (0%)	13
Total	17 (30%)	19 (33%)	13 (23%)	3 (5%)	5 (9%)	57

7.3.6 Falcon Business Jets

Table 7-24. Pilot Compliance (*Method A*) – Falcon Business Jets.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Descend	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Level Off (upward)	11 (79%)	0 (0%)	2 (14%)	1 (7%)	14
Level Off (downward)	5 (25%)	1 (5%)	14 (70%)	0 (0%)	20
Total	16 (42%)	5 (13%)	16 (42%)	1 (3%)	38

Table 7-25. Pilot Compliance (*Method B*) – Falcon Business Jets.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	2 (100%)	0 (0%)	0 (0%)	0 (0%)	2
Descend	0 (0%)	1 (50%)	1 (50%)	0 (0%)	0 (0%)	2
Level Off (upward)	10 (71%)	3 (21%)	0 (0%)	0 (0%)	1 (7%)	14
Level Off (downward)	11 (55%)	8 (40%)	1 (5%)	0 (0%)	0 (0%)	20
Total	21 (55%)	14 (37%)	2 (5%)	0 (0%)	1 (3%)	38

7.3.7 Bombardier Regional Jets

Table 7-26. Pilot Compliance (*Method A*) – Bombardier Regional Jets.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	3 (60%)	1 (20%)	0 (0%)	1 (20%)	5
Descend	1 (25%)	1 (25%)	2 (50%)	0 (0%)	4
Level Off (upward)	1 (50%)	0 (0%)	1 (50%)	0 (0%)	2
Level Off (downward)	9 (50%)	1 (6%)	8 (44%)	0 (0%)	18
Total	14 (48%)	3 (10%)	11 (38%)	1 (4%)	29

Table 7-27. Pilot Compliance (*Method B*) – Bombardier Regional Jets.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	3 (60%)	0 (0%)	1 (20%)	0 (0%)	1 (20%)	5
Descend	1 (25%)	2 (50%)	1 (25%)	0 (0%)	0 (0%)	4
Level Off (upward)	2 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	2
Level Off (downward)	11 (61%)	7 (39%)	0 (0%)	0 (0%)	0 (0%)	18
Total	17 (59%)	9 (31%)	2 (7%)	0 (0%)	1 (3%)	29

7.3.8 Boeing 737-300/400/500

Table 7-28. Pilot Compliance (*Method A*) – Boeing 737-300/400/500.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	3 (75%)	1 (25%)	0 (0%)	4
Descend	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1
Level Off (upward)	6 (60%)	1 (10%)	3 (30%)	0 (0%)	10
Level Off (downward)	6 (46%)	2 (15%)	4 (31%)	1 (8%)	13
Total	12 (43%)	7 (25%)	8 (28%)	1 (4%)	28

Table 7-29. Pilot Compliance (*Method B*) – Boeing 737-300/400/500.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	2 (50%)	2 (50%)	0 (0%)	0 (0%)	4
Descend	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1
Level Off (upward)	8 (80%)	1 (10%)	1 (10%)	0 (0%)	0 (0%)	10
Level Off (downward)	7 (54%)	5 (38%)	0 (0%)	0 (0%)	1 (8%)	13
Total	15 (54%)	9 (32%)	3 (10%)	0 (0%)	1 (4%)	28

7.3.9 Boeing 757 and 767

Table 7-30. Pilot Compliance (*Method A*) – Boeing 757 and 767.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Descend	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Level Off (upward)	2 (25%)	0 (0%)	5 (63%)	1 (12%)	8
Level Off (downward)	5 (36%)	1 (7%)	8 (57%)	0 (0%)	14
Total	7 (27%)	5 (19%)	13 (50%)	1 (4%)	26

Table 7-31. Pilot Compliance (*Method B*) – Boeing 757 and 767.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	1 (50%)	1 (50%)	0 (0%)	0 (0%)	2
Descend	0 (0%)	2 (100%)	0 (0%)	0 (0%)	0 (0%)	2
Level Off (upward)	3 (38%)	3 (38%)	1 (12%)	0 (0%)	1 (12%)	8
Level Off (downward)	7 (50%)	6 (43%)	1 (7%)	0 (0%)	0 (0%)	14
Total	10 (39%)	12 (46%)	3 (11%)	0 (0%)	1 (4%)	26

7.3.10 Boeing 777

Table 7-32. Pilot Compliance (*Method A*) – Boeing 777.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	1 (50%)	1 (50%)	0 (0%)	2
Descend	1 (50%)	1 (50%)	0 (0%)	0 (0%)	2
Level Off (upward)	5 (39%)	3 (22%)	5 (39%)	0 (0%)	13
Level Off (downward)	2 (29%)	1 (14%)	4 (57%)	0 (0%)	7
Total	8 (33%)	6 (25%)	10 (42%)	0 (0%)	24

Table 7-33. Pilot Compliance (*Method B*) – Boeing 777.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	2 (100%)	0 (0%)	0 (0%)	0 (0%)	2
Descend	1 (50%)	1 (50%)	0 (0%)	0 (0%)	0 (0%)	2
Level Off (upward)	8 (62%)	5 (38%)	0 (0%)	0 (0%)	0 (0%)	13
Level Off (downward)	3 (43%)	4 (57%)	0 (0%)	0 (0%)	0 (0%)	7
Total	12 (50%)	12 (50%)	0 (0%)	0 (0%)	0 (0%)	24

7.3.11 Airbus A330 and A340

Table 7-34. Pilot Compliance (*Method A*) – Airbus A330 and A340.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1
Descend	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Level Off (upward)	4 (34%)	1 (8%)	7 (58%)	0 (0%)	12
Level Off (downward)	3 (37%)	2 (25%)	3 (38%)	0 (0%)	8
Total	7 (33%)	4 (19%)	10 (48%)	0 (0%)	21

Table 7-35. Pilot Compliance (*Method B*) – Airbus A330 and A340.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1
Descend	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Level Off (upward)	9 (75%)	3 (25%)	0 (0%)	0 (0%)	0 (0%)	12
Level Off (downward)	4 (50%)	4 (50%)	0 (0%)	0 (0%)	0 (0%)	8
Total	13 (62%)	8 (38%)	0 (0%)	0 (0%)	0 (0%)	21

7.3.12 Dash 8

Table 7-36. Pilot Compliance (*Method A*) – Dash 8.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	4 (57%)	3 (43%)	0 (0%)	0 (0%)	7
Descend	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Level Off (upward)	0 (0%)	0 (0%)	1 (50%)	1 (50%)	2
Level Off (downward)	4 (57%)	2 (29%)	0 (0%)	1 (14%)	7
Total	8 (50%)	5 (31%)	1 (6%)	2 (13%)	16

Table 7-37. Pilot Compliance (*Method B*) – Dash 8.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	4 (57%)	2 (29%)	1 (14%)	0 (0%)	0 (0%)	7
Descend	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0
Level Off (upward)	0 (0%)	0 (0%)	1 (50%)	0 (0%)	1 (50%)	2
Level Off (downward)	3 (43%)	2 (29%)	1 (14%)	0 (0%)	1 (14%)	7
Total	7 (44%)	4 (25%)	3 (19%)	0 (0%)	2 (12%)	16

7.3.13 Beechcraft Turboprops

Table 7-38. Pilot Compliance (*Method A*) – Beechcraft Turboprops.

	Followed	Not Followed	Opposite	Excessive	Total
Climb	0 (0%)	4 (50%)	4 (50%)	0 (0%)	8
Descend	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Level Off (upward)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	1
Level Off (downward)	1 (33%)	0 (0%)	2 (67%)	0 (0%)	3
Total	2 (14%)	6 (43%)	6 (43%)	0 (0%)	14

Table 7-39. Pilot Compliance (*Method B*) – Beechcraft Turboprops.

	Following	Weak Response	No Response	Opposite	Excessive	Total
Climb	0 (0%)	1 (12%)	7 (88%)	0 (0%)	0 (0%)	8
Descend	0 (0%)	0 (0%)	2 (100%)	0 (0%)	0 (0%)	2
Level Off (upward)	1 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1
Level Off (downward)	2 (67%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)	3
Total	3 (21%)	2 (14%)	9 (65%)	0 (0%)	0 (0%)	14

Given that the input data is prone to some error and the size of some aircraft groups is quite small, there is little to distinguish between many of the aircraft groups when it comes to pilot compliance. There is no clear difference between Airbus and Boeing for instance. Pilot compliance for the Embraer Regional Jet group stands out as potentially the best, with a compliance rate of 61.5% (*Method A*) and for *Method B*, a 'following' rate of 71.8%. The two poorest performing categories are 'Cessna Business Jets' and 'Beechcraft Turboprops'; however, the sample size is too low to determine reliably whether it is by chance or a sign of a systemic problem.

8 Conclusions (pilot compliance with TCAS RAs)

Version 1 of this report concluded that a significant proportion of RAs are not flown correctly. This conclusion was based upon the *Method A* compliance assessment scheme. *Method B* draws a similar conclusion, although the precise results are different, and gives some credit to pilots following the RA even if the required rate is not yet achieved.

In summary, the overall compliance rates using the two methods are (see Figure 8-1):

- *Method A*, at 8 seconds: 37.9%
- *Method A*, at 12 seconds: 55.1%
- *Method B*, at 8 seconds: 55.0%
- *Method B*, at 12 seconds: 53.7%

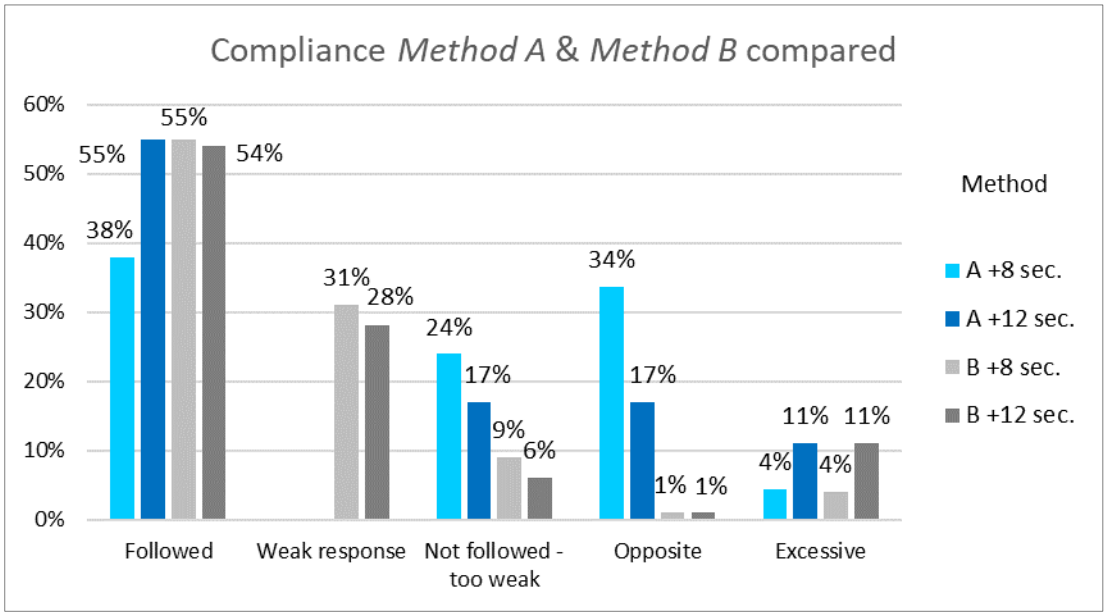

Figure 8-1. Compliance *Method A* & *Method B* compared.

Method B also detects 'weak compliance' – these are aircraft manoeuvring in the required vertical direction, but not quickly enough or with insufficient rate. Under the *Method B* scheme, a further 31.4% of pilots are weakly following the RA at 8 seconds and 28.4% at 12 seconds after the RA is triggered.

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 risk (as indicated by simulations of TCAS in safety studies).

Compared to *Method A*, *Method B* indicates significantly fewer cases where the pilot is assessed to be not responding to the RA at all, or to be responding in the opposite sense. Further study, using airborne data, may be needed to determine which of the two methods provides the better assessment of pilot responses. Nevertheless, it is

thought that *Method A* (due to the rigid approach) could be over-counting the number of opposite sense responses. This needs to be confirmed by the examination of airborne data.

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

For Climb and Descend RAs, regardless of the method and regardless of whether the assessment was at 8, 12 or 16 seconds after the RA, the compliance never exceeded 33%. Under *Method A*, approximately half of the pilots did not achieve the required vertical rate, so their response was classified as “not followed”. Under *Method B*, approximately 40% of pilots were credited with following the RA ‘weakly’, and opposite responses were around 5%.

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, provide them with a feedback regarding their RA performance and to take corrective measures as necessary.

With regard to pilot compliance performance and any dependency on the vertical attitude (climb, level or descent) at the time of the RA, for Climb and Descend RAs the compliance rate appears to be better when the RA is in the same vertical direction as the vertical attitude of the aircraft RA. For Level Off RAs, there is no clear trend in pilot compliance versus vertical attitude.

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

No significant performance differences were observed while comparing crews of EASA-country registered aircraft vs non-EASA aircraft.

Examination of various aircraft operations categories has concluded that airline pilots are generally better at compliance with the RA than other operations.

There is little to distinguish between the various aircraft type groups / families. However, Embraer Regional Jets do stand out as being a little better than other aircraft groups, and Cessna business jets and Beechcraft turbojets a little worse. However, caution should be exercised given the relatively small samples in some of these groupings.

9 Assessment of TCAS operating mode selection

A selector switch on the transponder panel allows the pilot to select one of the three TCAS II operating modes (implementation details can vary, especially if TCAS and transponder panels are combined): Stand-by (or Off); TA-only; and TA/RA.

The normal operating mode of TCAS II is TA/RA. In this mode TCAS II will provide full safety protection issuing TAs and RAs, as needed. The TA-only mode is allowed only in certain aircraft performance limiting conditions caused by in-flight failures (e.g. engine failure) or TCAS equipment failures, as permitted by MEL. Other TCAS-equipped aircraft can generate uncoordinated RAs against a TA-only aircraft, which will be treated as an unequipped aircraft. As the operations in TA-only mode deny the aircraft of TCAS II collision avoidance protection, it has been decided to assess the scale of the TA-only operations in core European airspace.

A subset of data used for the above mentioned pilot compliance study has been used to assess if the aircraft were operated in the TA-only mode. Radar recordings were analysed for a recording period spanning 14 days. Specifically, the downlinked Mode S BDS1,0 registers were examined. The BDS1,0 register provides to the ground information on the TCAS operational status. If TCAS II is set in TA-only mode that will be indicated accordingly.

In some situations, pilots switch to TA-only mode for short periods of time. Typically, that occurs during parallel approaches to avoid unwanted RAs with an aircraft against which visual separation is maintained. For that reason, any BDS1,0 messages indicating TA-only mode operations below FL100 or less than 5 minutes were excluded from analysis.

In the examined 14-day period there were 122,068 flights that delivered BDS1,0 messages. In 696 cases (0.6%), the BDS1,0 messages reported TA-only mode. The 696 cases represented 0.1% of flight hours in the examined period. The collected messages and flight hours included only airline flights. Military and general aviation have been excluded.

9.1 Flights in TA-only mode per day

Table 9-1 below indicates the number of aircraft operating in TA-only mode at or above FL100 for 5 minutes or more each day of the 14-day observation period. For reference, the total number of flights and flight hours on each day are provided.

While it is a small percentage of all operations, these aircraft may have not benefited from the protection offered by TCAS II RAs. It is believed that the majority of these operations were due to incorrect mode selection by the crew. Technical malfunctions, like transponder fault or incorrect Mode S BDS1,0 downlink, cannot be excluded, especially in the case of TA-only mode operations for more than one day. These malfunctions will most likely will be unknown to the crew.

Table 9-1. TCAS was switched to TA only mode – the summary from each day.

Day	Aircraft in TA only	Total flights	Hours in TA-only	Total hours
1	55	9488	17	18125
2	64	8978	17	17458
3	60	9379	18	17663
4	36	9359	10	17295
5	40	8656	11	16075
6	47	8562	12	16917
7	59	8041	17	16005
8	43	7352	12	14955
9	58	8403	17	16115
10	47	10053	11	18950
11	42	10454	12	19353
12	43	8797	12	16286
13	45	7031	14	14284
14	57	7515	12	14627

The pilots and aircraft operators should ensure that the TCAS equipment remains in TA/RA mode throughout the flight. If TCAS is in Standby mode, it is likely that the pilot will spot this, as no surrounding traffic will be visible on the TCAS traffic display. Although cockpit alerts may be provided (implementation depended) to notify the crew if the TA-only mode is selected in flight, this condition might not be noticed, as the surrounding traffic will be displayed.

9.2 Flight in TA-only mode per airframe

During the 14-days when the data was collected, TA-only mode was observed on 291 individual aircraft for a period not exceeding one day. Altogether, TA-only mode was observed on 414 unique aircraft, on some for as long as 10 days. Downlink reports of TA-only mode for any extended period of time on the same aircraft are most likely an indication of a technical problem rather than a human error in the TCAS mode selection.

The number of unique airframe observation per observation day is shown in Table 9-2.

Table 9-2. Flight in TA-only mode per airframe.

Number of days	Number of airframes	Percentage of frames
1	291	70.3%
2	50	12.1%
3	37	8.9%
4	17	4.1%
5	7	1.7%
6	5	1.2%
7	2	0.5%
8	1	0.2%
9	1	0.2%
10	3	0.7%
11	0	0.0%
12	0	0.0%
13	0	0.0%
14	0	0.0%
Total	414	100.0%

9.3 Flights in TA-only mode per aircraft type

Table 9-3 below shows the most frequent 60% of aircraft types or aircraft type family recorded operating in TA-only mode for one day only during the observation period.

Table 9-3. Flights in TA-only mode per aircraft type.

Aircraft type / type family	Number of occurrences
Airbus A320 Family (A319, A320, A321)	66
Boeing 737-800	42
Boeing 757 & 767 (all series)	21
Bombardier Regional Jets (CRJ2, CRJ7, CRJ9, CRJX)	17
Hawker (H25B)	15
Airbus A330 & A340	13
Total	**174**

10 Assessment of TCAS Serviceability

Similarly, the BDS1,0 messages can be used to assess the number of flight operating with TCAS II out of service, switched off or not installed. In the 14-day period there were such 1715 flights (1.4%). To exclude any transient problems, only flights reporting unserviceable TCAS for more than 5 minutes were counted. Again, only airline flights were taken into statistics.

Table 10-1. Cases when TCAS was deactivated – the summary from each day.

Day	Flights with TCAS not operating	Total number of flights
1	138	9488
2	149	8978
3	145	9379
4	85	9359
5	99	8656
6	120	8562
7	146	8041
8	136	7352
9	148	8403
10	138	10053
11	82	10454
12	93	8797
13	121	7031
14	115	7515

Operations with TCAS out of service are allowed under the provision of Minimum Equipment List (MEL). In most of the cases in Europe an aircraft may operate under the MEL provisions with TCAS II inoperative for up to 10 calendar days. However, in German airspace the time period is reduced to 3 days. Neither TAs nor RAs will be received by the aircraft operating without serviceable TCAS II.

The recording captured 14 aircraft reporting unserviceable TCAS each day of the examined period, 20 for 10 days or more, 72 for 7 days or more, and 126 for 5 days or more. While it is understood that sometimes an aircraft can be dispatched without the serviceable TCAS equipment, any prolonged periods of unserviceability as well as large numbers of aircraft operating under the MEL exemption, are a source of concern, as these aircraft will not benefit from the protection offered by TCAS.

11 Abbreviations, Glossary and References

11.1 Abbreviations

ACAS – Airborne Collision Avoidance System
ATC – Air Traffic Control
BDS – Comm-B Data Selector
CPA – Closest Point of Approach
HMD – Horizontal Miss Distance
IATA – International Air Transport Association
ICAO – International Civil Aviation Organization
MEL – Minimum Equipment List
RA – Resolution Advisory
TA – Traffic Advisory
TCAS – Traffic Alert and Collision Avoidance System
VMD – Vertical Miss Distance

11.2 Glossary of terms

For more definitions and information refer to the EUROCONTROL ACAS Guide.

Closest Point of Approach (CPA) – The occurrence of minimum (slant) range between own ACAS aircraft and the intruder. Range at CPA is the smallest range between the two aircraft and time at CPA is the time at which it occurs.

Horizontal Miss Distance (HMD) – the horizontal range between two aircraft at the Closest Point of Approach.

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

Reversed sense (reversal) 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 descent) can be strengthened to either Increase Climb or Increase Descent RAs.

Vertical Miss Distance (VMD) – the relative altitude between own and intruder aircraft at closest point of approach.

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

11.3 References

IATA/EUROCONTROL Guidance Material on Performance assessment of pilot compliance to Traffic Alert and Collision Avoidance System (TCAS) using Flight Data Monitoring (FDM), 3rd edition, January 2022.

EUROCONTROL ACAS Guide, December 2017

TCAS RA not Followed, Network Manager Operational Safety Study, EUROCONTROL, September 2017.

EUROCONTROL: Traffic Alert and Collision Avoidance System (TCAS) – Selected Statistical and Performance Data in Core European Space, February 2020

Annex 1 Algorithm of *Method B* Pilot Compliance Scheme

An alternative compliance scheme (*Method B)* makes the following assumptions:

- The pilot has to process and respond to the RA and is allowed a time budget of 5 seconds to start the required manoeuvre;
- When following the RA, the pilot is expected to maintain a vertical acceleration of 0.25*g*;
- The vertical rates provided in the radar recordings are subject to noise / altitude quantisation and tracker lag; therefore to take account of this imperfect data a vertical rate tolerance of ±300 ft/min is allowed for in the assessment of pilot compliance.

We start by defining the following:

- Vrate_RA is the vertical rate at the time of the RA;
- Vrate_8s is the vertical rate 8 seconds after the RA;
- Vrate_12s is the vertical rate 12 seconds after the RA;

These are the metrics available in the data recordings.

Unless otherwise stated, units for all vertical rates are in feet per minute (ft/min). Vertical acceleration is in ft/min/s. The expected vertical acceleration for RA compliance is 0.25*g*; in the units used in this section, this is 482.61 ft/min/s.

A key part of this algorithm is the concept of a target vertical rate, based upon either a computed achievable vertical rate or the vertical rate required by the RA (i.e. the rate denoted by the green arc on the vertical speed indicator, or the pitch-cue on the primary flight display).

If the vertical rate required by the RA isn't actually achievable at the specific measurement interval (e.g. RA + 8 seconds) then the pilot may still be 'following' the RA as long as the achievable vertical rate is met.

Another key concept is the idea of a vertical rate tolerance, which takes account of the inaccuracy of the vertical rate data being used as input to the analysis. This tolerance gives the pilot the benefit of the doubt if the vertical rate is close to that required. For instance a Climb RA would require the pilot to achieve a vertical rate of 1500 ft/min. However, in this scheme (as also in the IATA/EUROCONTROL guidance), a tolerance of 300 ft/min is applied. This means that a pilot exceeding 1200 ft/min is deemed to be following the RA.

For all Climb, Descend and Level Off RAs, the pilot is allowed 5 seconds reaction time. At the 8 second sample interval, only 3 seconds of acceleration (at 482.61 ft/min/s) is budgeted for in calculated the achievable vertical rate.

The achievable vertical rate at 8 seconds is computed as follows:
For Climb or Level Off 'upward sense' RAs:

$$\text{Achievable\_vertical\_rate\_8s} = \text{Vrate\_RA} + (3\text{s} \times 482.61\ \text{ft/min/s}) - 300\ \text{ft/min}$$

For Descend or Level Off 'downward sense' RAs:

$$\text{Achievable\_vertical\_rate\_8s} = \text{Vrate\_RA} - (3\text{s} \times 482.61\ \text{ft/min/s}) + 300\ \text{ft/min}$$

Note that the achievable vertical rate has the 300 ft/min tolerance included.

The achievable vertical rate at 12 seconds is computed in a very similar manner. In this case, 7 seconds (12 minus 5 seconds) is available for the acceleration period.

For Climb or Level Off 'upward sense' RAs:

$$\text{Achievable\_vertical\_rate\_12s} = \text{Vrate\_RA} + (7\text{s} \times 482.61\ \text{ft/min/s}) - 300\ \text{ft/min}$$

For Descend or Level Off 'downward sense' RAs:

$$\text{Achievable\_vertical\_rate\_12s} = \text{Vrate\_RA} - (7\text{s} \times 482.61\ \text{ft/min/s}) + 300\ \text{ft/min}$$

The target vertical is then computed based upon the achievable vertical rate and the final vertical rate required by the RA.

For instance, the target vertical rate for a Climb RA is the minimum of the achievable vertical rate and 1200 ft/minute. In pseudo code notation:

$$\text{target\_vertical\_rate\_8s} = \text{MIN}(\text{achievable\_vertical\_rate\_8s}, 1200\ \text{ft/min}).$$

and similarly,

$$\text{target\_vertical\_rate\_12s} = \text{MIN}(\text{achievable\_vertical\_rate\_12s}, 1200\ \text{ft/min}).$$

The table below summarises the target vertical rate calculations for all RA types:

Climb RA (RA + 8 sec.)	MIN (achievable_vertical_rate_8s, 1200)
Climb RA (RA + 12 sec.)	MIN (achievable_vertical_rate_12s, 1200)
Descend RA (RA + 8 sec.)	MAX (achievable_vertical_rate_8s, –1200)
Descend RA (RA + 12 sec.)	MAX (achievable_vertical_rate_12s, –1200)
Level Off (upward sense) (RA + 8 sec.)	MIN (achievable_vertical_rate_8s, –300)
Level Off (upward sense) (RA + 12 sec.)	MIN (achievable_vertical_rate_12s, –300)
Level Off (downward sense) (RA + 8 sec.)	MAX (achievable_vertical_rate_8s, 300)
Level Off (downward sense) (RA + 12 sec.)	MAX (achievable_vertical_rate_12s, 300)

Table A-1: Target Vertical Rate computation for all RAs.

Once the target_vertical_rate_8 seconds and target_vertical_rate_12 seconds have been calculated, the assessment is then made as to whether the pilot is following the RA, or whether the response is weak, excessive, opposite to what is required, or if there is no marked response at all.

For Climb RAs (RA+8 sec.):

'Following' is assigned if Vrate_8s > target_vertical_rate_8s
AND Vrate_8s <= 2200ft/min;

'Weak Response': if Vrate_8s > Vrate_RA + 300ft/min
AND Vrate_8s <= target_vertical_rate_8s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_8s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_8s < Vrate_RA – 300 ft/min;

'Excessive Response' is assigned if Vrate_8s > 2200 ft/min;

For Climb RAs (RA+12 sec.):

'Following' is assigned if Vrate_12s > target_vertical_rate_12s
AND Vrate_12s <= 2200 ft/min;

'Weak Response': if Vrate_12s > Vrate_RA + 300 ft/min
AND Vrate_12s <= target_vertical_rate_12s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_12s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_12s < Vrate_RA – 300 ft/min;

'Excessive Response' is assigned if Vrate_12s > 2200 ft/min;

For Descend RAs (RA+8 sec.):

'Following' is assigned if Vrate_8s < target_vertical_rate_8s
AND Vrate_8s >= –2200 ft/min;

'Weak Response': if Vrate_8s < Vrate_RA – 300 ft/min
AND Vrate_8s >= target_vertical_rate_8s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_8s is with ± 300ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_8s > Vrate_RA + 300 ft/min;

'Excessive Response' is assigned if Vrate_8s < –2200 ft/min;

For Descend RAs (RA+12s):

'Following' is assigned if Vrate_12s < target_vertical_rate_12s
AND Vrate_12s >= –2200 ft/min;

'Weak Response': if Vrate_12s < Vrate_RA – 300 ft/min
AND Vrate_12s >= target_vertical_rate_12s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_12s is with ± 300ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_12s > Vrate_RA + 300 ft/min;

'Excessive Response' is assigned if Vrate_12s < –2200 ft/min;

For Level Off RAs – upward sense (RA+8 sec.):

'Following' is assigned if Vrate_8s > target_vertical_rate_8s
AND Vrate_8s <= 500 ft/min;

'Weak Response': if Vrate_8s > Vrate_RA + 300 ft/min
AND Vrate_8s <= target_vertical_rate_8s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_8s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_8s < Vrate_RA – 300 ft/min;

'Excessive Response' is assigned if Vrate_8s > 500 ft/min;

For Level Off RAs – upward sense (RA+12 sec.):

'Following' is assigned if Vrate_12s > target_vertical_rate_12s
AND Vrate_12s <= 500 ft/min;

'Weak Response': if Vrate_12s > Vrate_RA + 300 ft/min
AND Vrate_12s <= target_vertical_rate_12s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_12s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_12s < Vrate_RA – 300 ft/min;

'Excessive Response' is assigned if Vrate_12s > 500 ft/min;

For Level Off RAs – downward sense (RA+8 sec.):

'Following' is assigned if Vrate_8s < target_vertical_rate_8s
AND Vrate_8s >= –500 ft/min;

'Weak Response': if Vrate_8s < Vrate_RA – 300f t/min
AND Vrate_8s >= target_vertical_rate_8s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_8s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_8s > Vrate_RA + 300 ft/min;

'Excessive Response' is assigned if Vrate_8s < -500 ft/min;

For Level Off RAs – downward sense (RA+12 sec.):

'Following' is assigned if Vrate_12s < target_vertical_rate_12s
AND Vrate_12s >= –500 ft/min;

'Weak Response': if Vrate_12s < Vrate_RA – 300 ft/min
AND Vrate_12s >= target_vertical_rate_12s;

If (and only if) neither of the above two conditions apply, tests are made for 'no response', 'opposite' or 'excessive'

'No Response' is assigned if Vrate_12s is with ± 300 ft/min of Vrate_RA;

'Opposite Response' is assigned if Vrate_12s > Vrate_RA + 300 ft/min;

'Excessive Response' is assigned if Vrate_12s < –500 ft/min;

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