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

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Abstract			
The main purpose of this document is to present the result of the 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 indicate 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.			
Author(s)			
Mateusz MICHALSKI, NMD/SAF Stanislaw DROZDOWSKI, NMD/SAF			
Contact Person(s)	Tel/email	Unit	
Stanislaw DROZDOWSKI	+32 2 729 37 60 stanislaw.drozdowski@eurocontrol.int	NMD/SAF	

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

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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*,
- To assess *TCAS operating mode selection and serviceability* (Annex 1 & 2).

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](#).

Key findings:

- In total, 1184 RAs were examined,
- The substantial number of RAs is not followed correctly,
- Compliance varies depending on RA type and duration and in the worst case the correct compliance was as low as 38%,
- The 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) have been improved. Conversely, for RA that were not followed correctly a deterioration of the achieved Vertical Miss Distance (and, consequently, safety) have been observed.

A supplementary assessment of *TCAS operating mode selection and serviceability* 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 the assessment of pilot compliance with TCAS RAs, TCAS mode selection and TCAS serviceability.

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

The current ATM Top 5 operational risk priorities are:

- Blind spot (conflict between aircraft in close proximity no 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 support the “TCAS RA not followed” operational risk in order to provide operational data assessing pilot responses to TCAS RA, as well as TCAS operational mode and serviceability. This study supplements the survey conducted in 2017 in which a significant number of pilots admitted that often RAs are not followed. Also, previous monitoring activities established that pilots often do not follow RAs correctly¹. To conduct this study, radar recordings from core European airspace 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 EVAIR Safety Bulletin no 14 (2010-2014)

2 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 the [Annex](#).

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

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

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

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

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

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

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

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

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

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

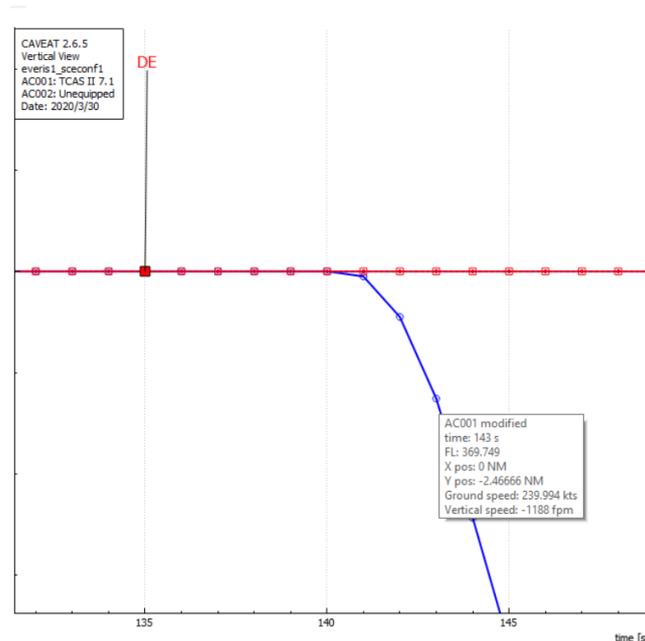


Figure 1: Simulation results 8 seconds after an RA was generated.

3 Limitations and assumptions

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

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

4 Results

Based on the [IATA/EUROCONTROL Guidance Material](#), pilot responses have been classified into following categories:

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

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

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

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

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

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

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

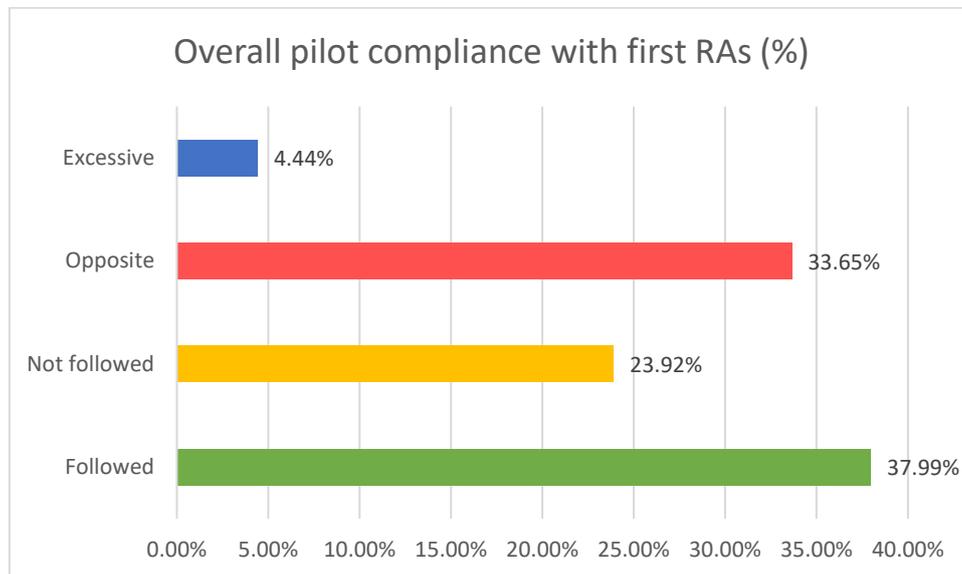


Figure 2. Pilot compliance with first RAs (%) - 8 seconds or longer.

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

4.1.1 Climb RAs – duration of 8 seconds or longer

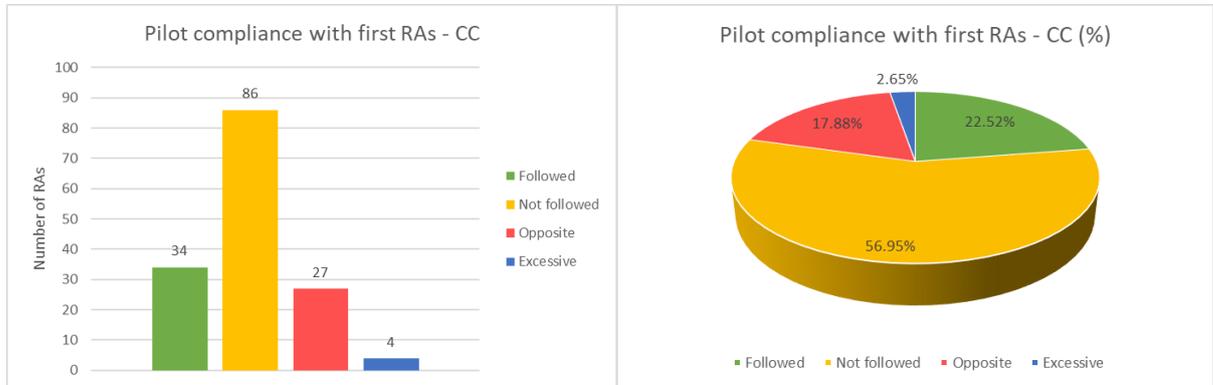


Figure 3. Pilot Compliance with first Climb RAs – 8 seconds or longer.

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

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

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

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

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

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

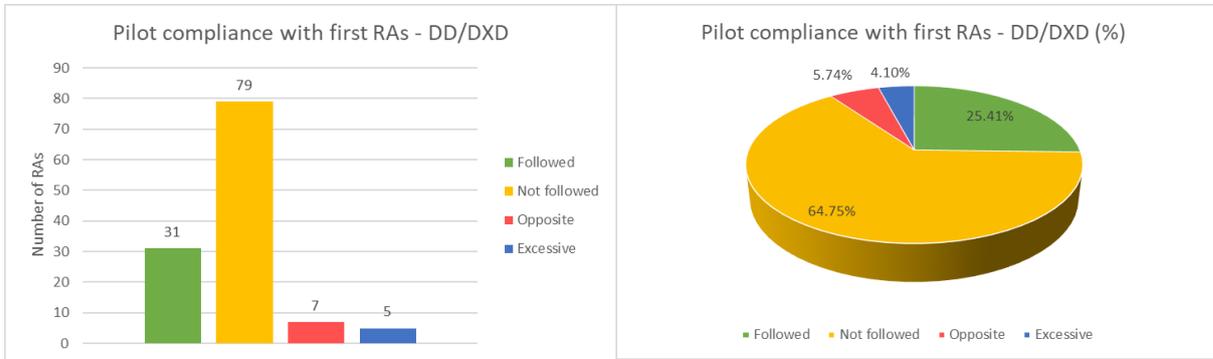


Figure 4. Pilot Compliance with first Descend/Crossing Descend RAs – 8 seconds or longer

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

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

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

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

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

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



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

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

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

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

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

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

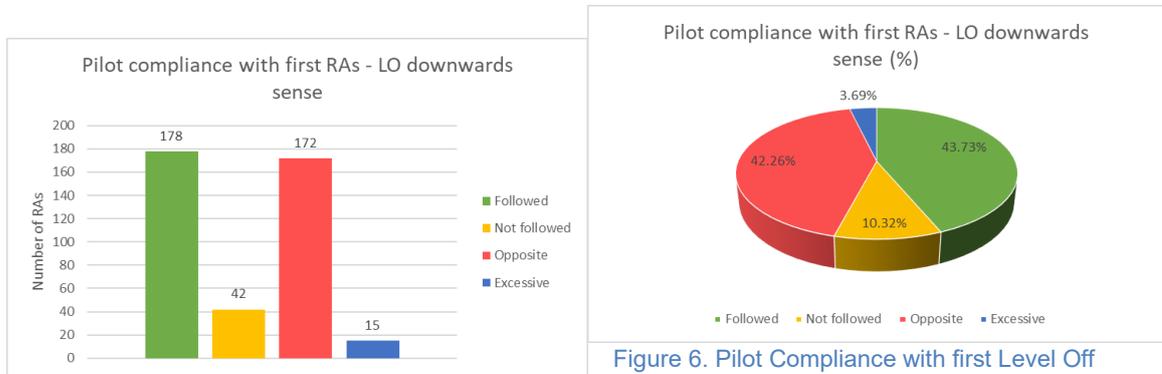


Figure 6. Pilot Compliance with first Level Off downwards sense RAs – 8 seconds or

longer.

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

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

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

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

4.1.5 Maintain Vertical Speed – duration of 8 seconds or longer

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

4.2 Secondary RAs – duration of 8 seconds or longer

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

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

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

Table 12. 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% = 171)
Climb	3 (27.27)	6 (54.55)	2 (18.18)	0 (0.00)	11 (6.43)
Reversal Climb	0 (00.00)	1 (50.00)	1 (50.00)	0 (00.00)	2 (1.17)
Increase Climb	1 (100.00)	0 (0.00)	0 (00.00)	0 (0.00)	1 (0.58)
Descend/Crossing Descend	3 (25.00)	6 (50.00)	2 (16.67)	1 (8.33)	12 (7.02)
Reversal Descend	2 (66.67)	0 (00)	0 (00.00)	1 (33.33)	3 (1.75)
Level Off – Upwards	43 (51.19)	1 (1.19)	3 (3.57)	37 (44.05)	84 (49.12)
Level Off – Downwards	28 (50.00)	0 (0.00)	0 (0.00)	27 (49.09)	55 (32.16)
Maintain Vertical Speed	2 (100.00)	0 (0.00)	0 (0.00)	0 (0.00)	2 (1.17)
Monitor Vertical Speed	Not assessed				1 (0.58)
Total (100% =171-Monitor Vertical Speed)	82 (48.24)	14 (8.24)	8 (4.71)	66 (38.82)	

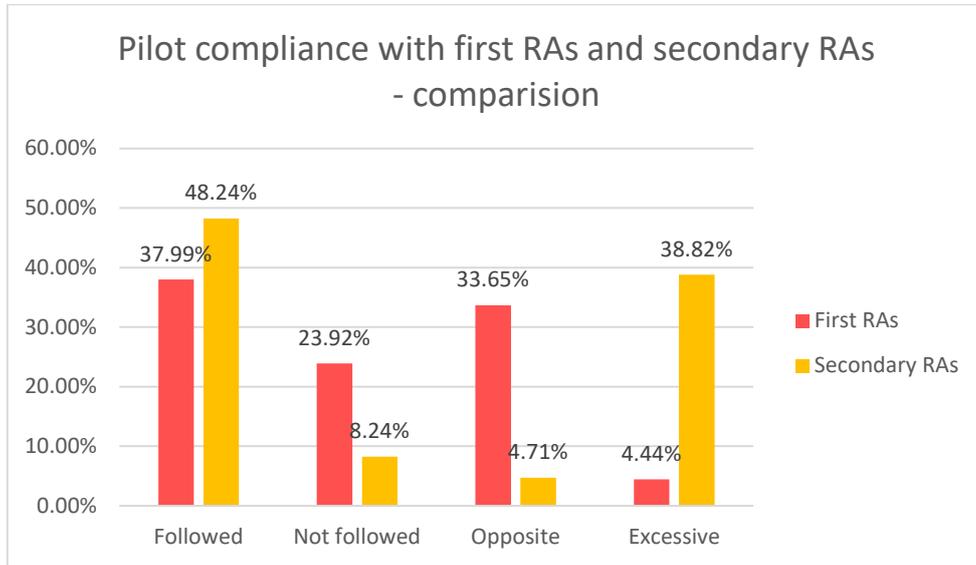


Figure 7. Pilot compliance with initial and secondary RAs – 8 seconds or longer.

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

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

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

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

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

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

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

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

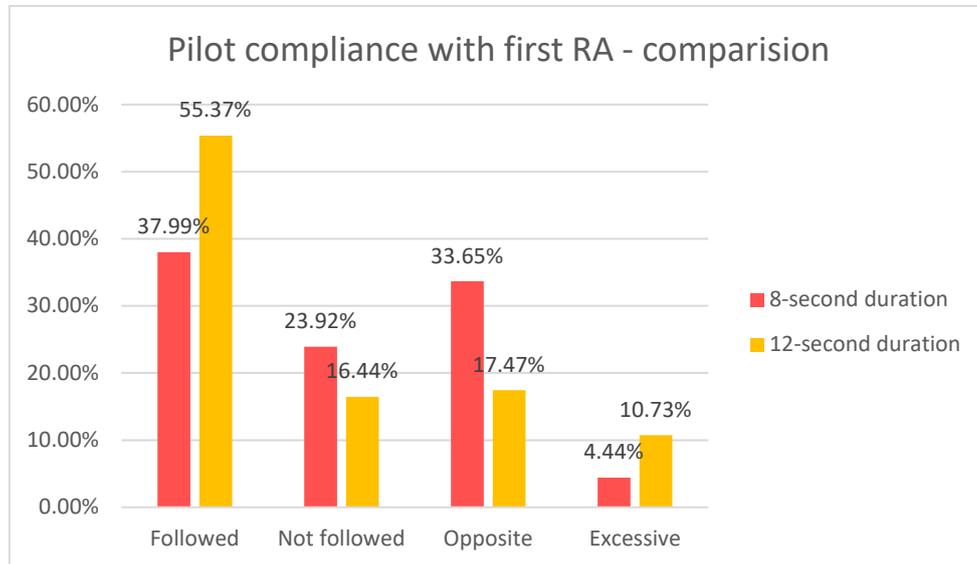


Figure 8. Pilot compliance with first RAs – comparison of the results.

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

4.4.1 Climb RA – duration of 12 seconds or longer

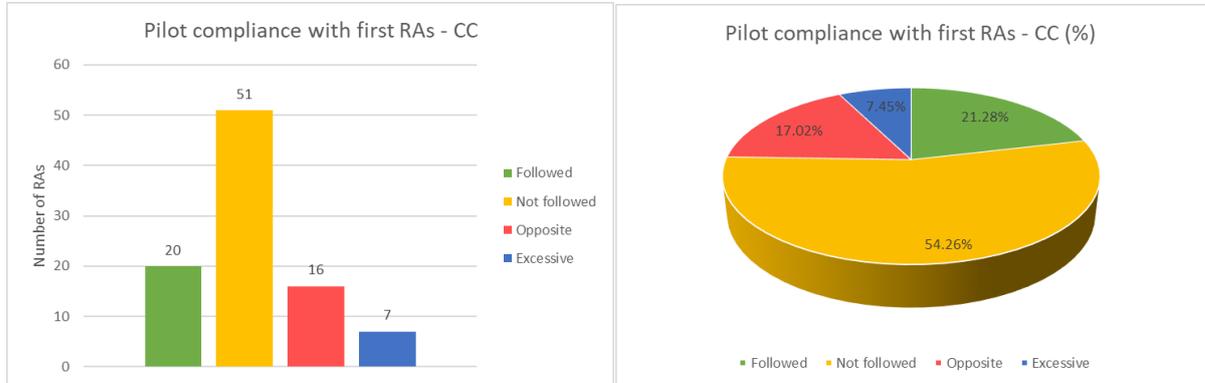


Figure 9. Pilot Compliance with first Climb RAs – 12 seconds or longer.

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

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

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

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

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

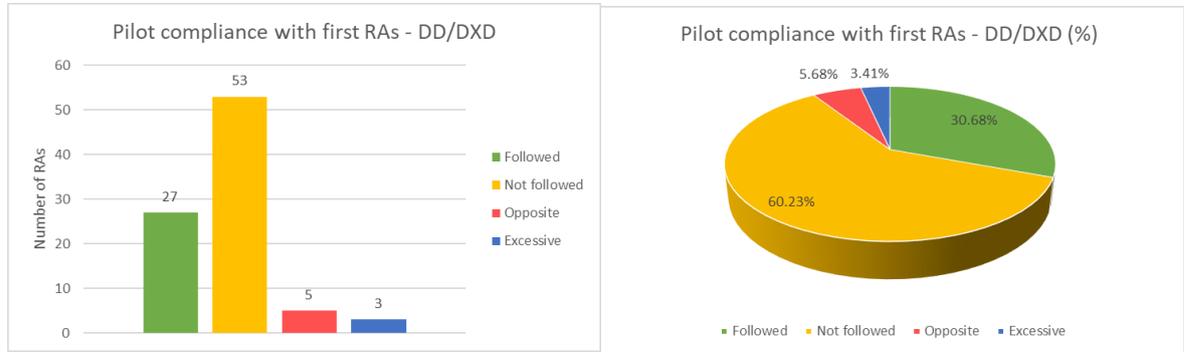


Figure 10. Pilot Compliance with first RAs – Descend/Crossing Descend – 12 seconds or longer.

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

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

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

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

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



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

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

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

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

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

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

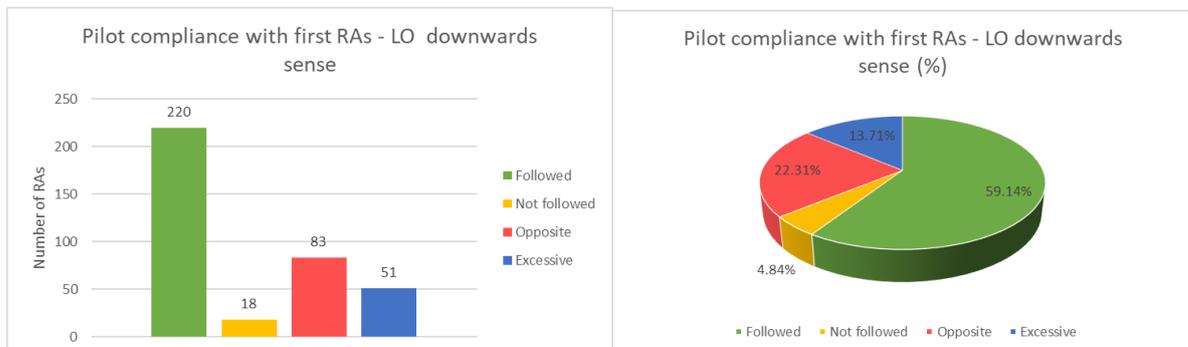


Figure 12. Pilot Compliance with first Level Off downwards sense RAs – 12 seconds or longer.

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

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

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

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

4.4.5 Maintain Vertical Speed – duration of 12 seconds or longer

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

4.5 Secondary RA – duration of 12 seconds or longer

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

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

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

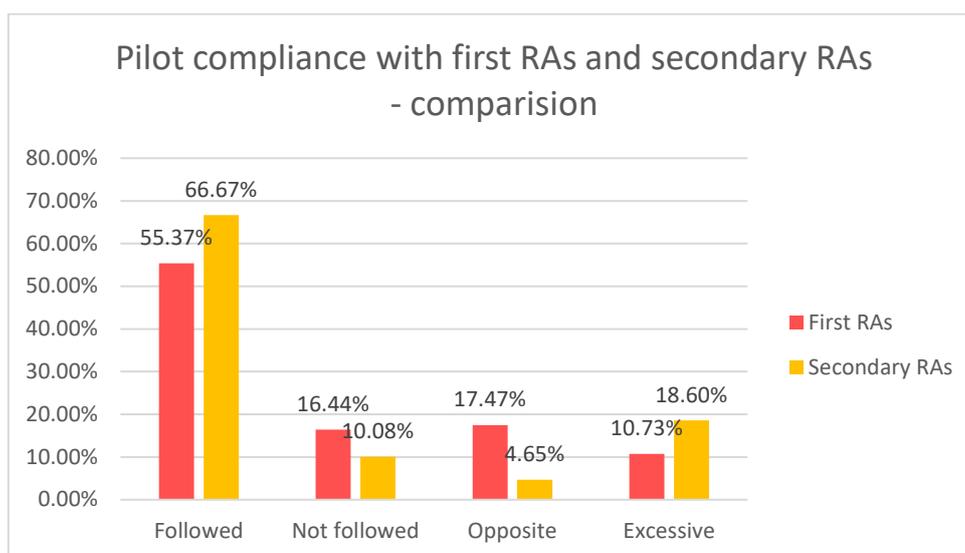


Figure 13. Pilot compliance with initial and secondary RAs – 12 seconds or longer.

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

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

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

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

4.7 Pilot compliance – duration of 16 seconds or longer

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

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

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

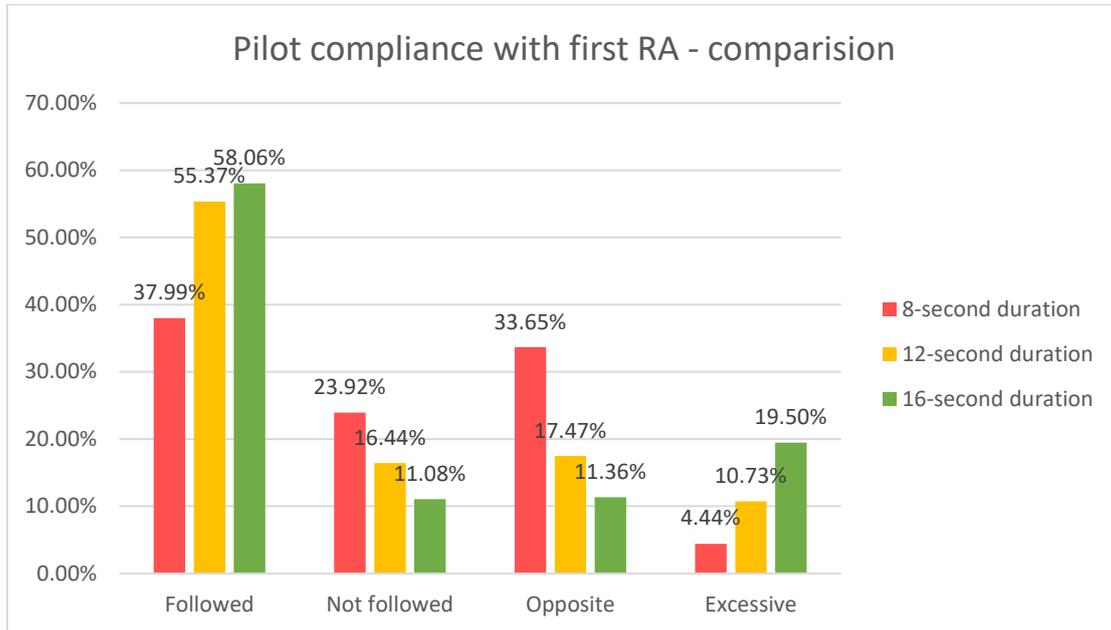


Figure 14. Pilot compliance with first RAs – comparison of the previous results.

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

4.7.1 Climb RA – duration of 16 seconds or longer

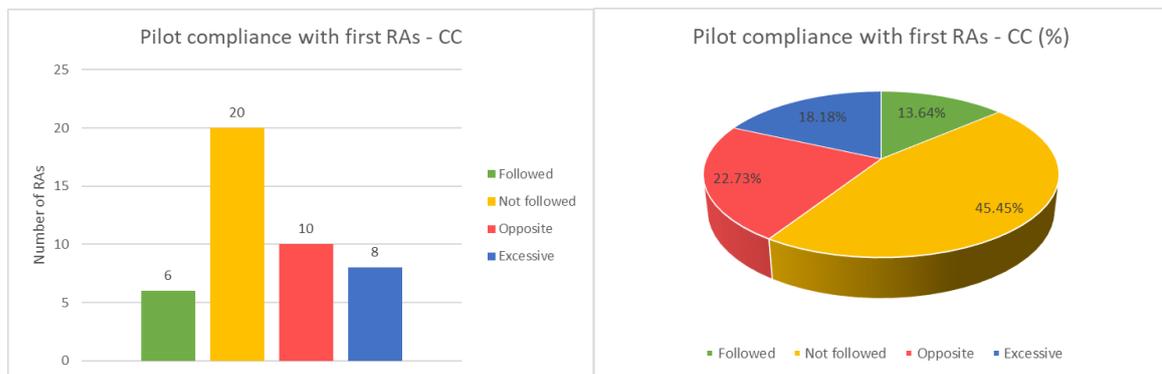


Figure 15. Pilot Compliance with first RAs – CC– 16 seconds or longer.

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

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

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

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

4.7.2 Descend RA – duration of 16 seconds or longer

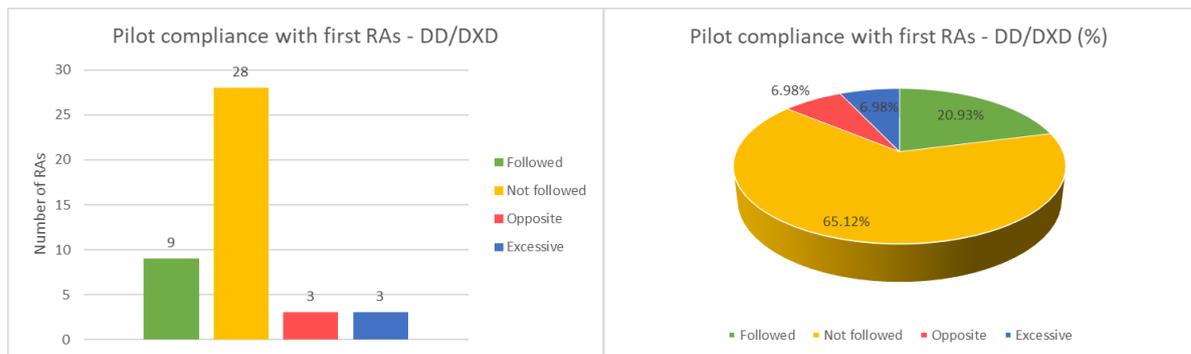


Figure 16. Pilot Compliance with first Descend/Crossing Descend RAs – 16 seconds or longer.

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

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

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

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

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

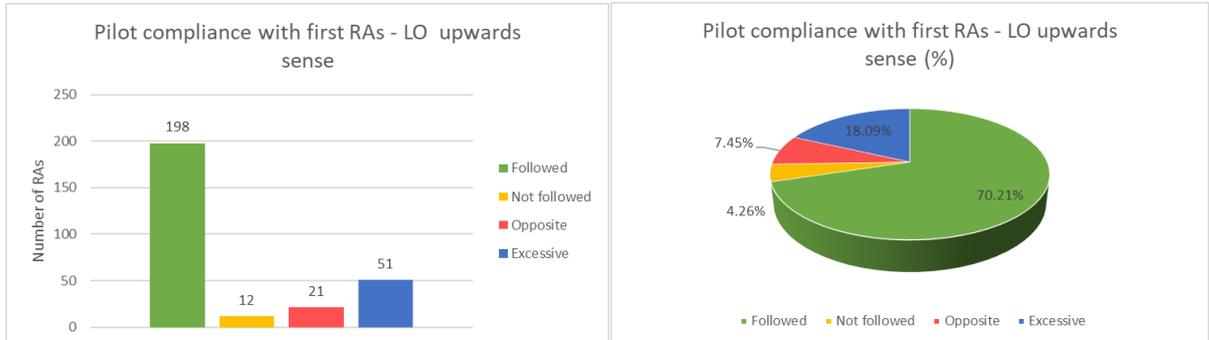


Figure 17. Pilot Compliance with first Level Off upwards RAs – 16 seconds duration.

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

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

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

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

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

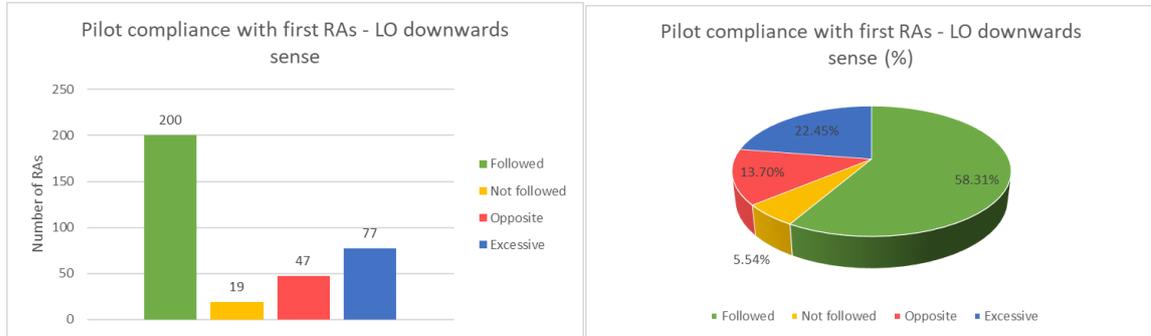


Figure 18. Pilot Compliance with first Level Off downward sense RAs –16 seconds or longer.

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

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

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

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

4.7.5 Maintain Vertical Speed – duration of 16 seconds or longer

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

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

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

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

5.1 Assumptions

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

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

5.2 Results

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

5.2.1 Vertical Miss Distances for Climb and Descend RAs

Table 34. VMD - Climb RA.

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

Table 35. VMD - Descend RAs.

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

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

5.2.2 Vertical Miss Distances for Level Off RAs

Table 36. VMD - Level Off upwards sense.

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

Table 37. VMD - Level Off, downwards sense.

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

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

The results attached in Table 37 are susceptible to misinterpretation. As shown to the table, the highest VMD values were achieved for *opposite* reactions. On the basis of the data in the table, the question might be raised whether *opposite* reactions are the

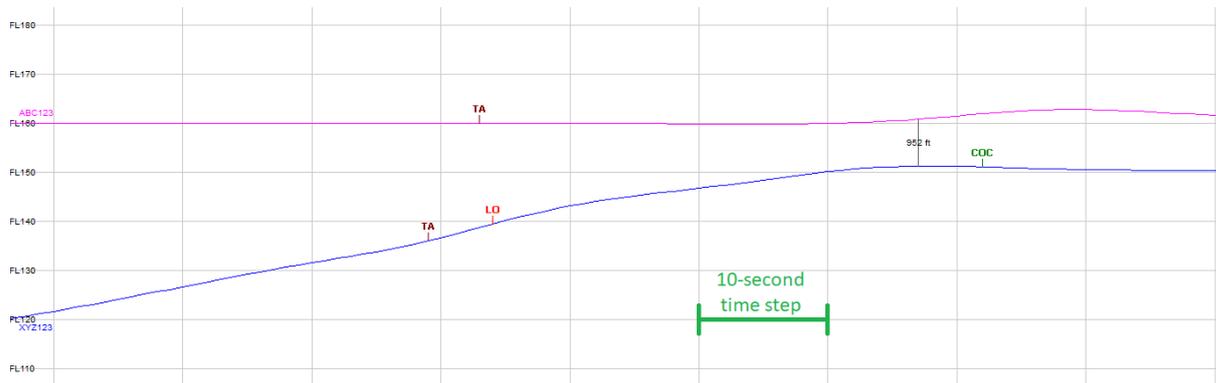
safest option in the subject of pilot compliance with Level Off RAs? Such a misleading conclusion could be drawn, but to comprehend this phenomenon correctly, several additional aspects need to be explained. According to the previous analysis, the substantial factor of *opposite* reactions is because pilots' response is far longer than assumed 8-second threshold. The number of *opposite* reactions is significantly reduced each time the minimum time for compliance with RAs is extended (see Table 38).

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

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

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

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



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

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

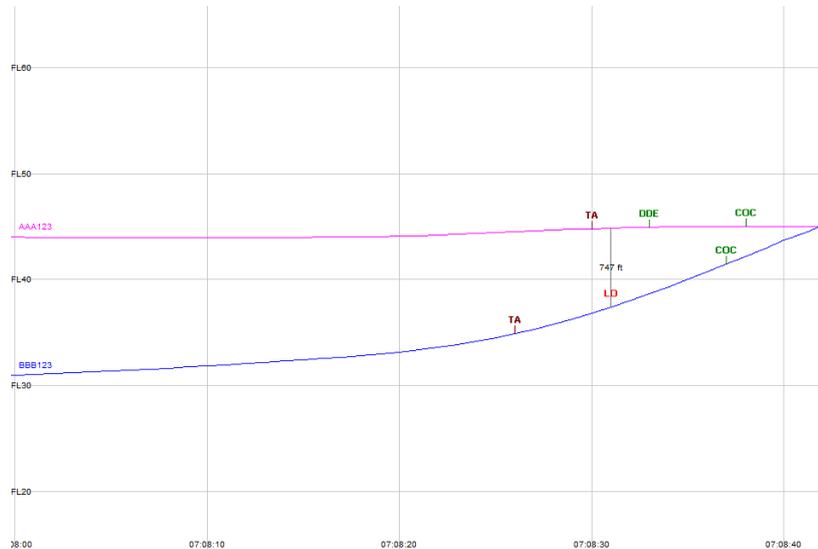


Figure 20. The example of an RA, which is not followed.

6 Conclusions (pilot compliance with TCAS RAs)

The study has shown that a significant proportion of RAs are not flown correctly. These results are line with anecdotal evidence from various sources. The study is not well placed to determine directly whether safety is degraded when pilots do not follow RAs correctly. However, it can be assumed that any incorrect responses to RAs may fail to resolve a collision (as indicated by simulations of TCAS in safety studies).

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

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

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

for aircraft operators to monitor carefully performance of their crews and to take corrective measures as necessary.

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

Annex 1

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. A TA-only aircraft will be treated as unequipped by other TCAS II aircraft. 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. For the period of 14-days the recordings of downlinked Mode S BDS1,0 register were analysed. 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 pertained only airline flights, military and GA has been excluded.

Table 39. TCAS was switched to TA only mode – the summary from each day.

Day	Aircraft in TA only	Total flights	Hours in TA	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

While it is a small percentage of all operations, these aircraft did not benefit from the protection offered by TCAS II RAs. It is believed that the majority of these operations were due incorrect mode selection by the crew.

While pilots may easily spot if TCAS is in Standby mode as no surrounding traffic will be visible on the TCAS traffic display, the incorrect selection of TA-only might be more difficult to notice, as the surrounding traffic will be displayed. The pilots and aircraft operators should ensure that the TCAS equipment remains in TA/RA mode throughout the flight.

Annex 2

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 40. Cases when TCAS was deactivated – the summary from each day.

Day	Flights with TCAS not operating	The 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 of 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 ACAS.

Abbreviations

ACAS – Airborne Collision Avoidance System
 ATC – Air Traffic Control
 BDS – Comm-B Data Selector
 CC – Climb RA
 COC – Clear of Conflict
 CCN – Reversal Climb RA
 CXC – Crossing Climb RA
 CPA – closest point of approach
 DD – Descend RA
 DDN – Reversal Descend RA
 DXD – Crossing Descend RA

HMD – Horizontal Miss Distance
IATA – International Air Transport Association
IC – Increase Climb RA
ID – Increase Descent RA
ICAO – International Civil Aviation Organization
LO – Level Off RA
MEL – Minimum Equipment List
MVS – Monitor Vertical Speed RA
MVSCM – Maintain Vertical Speed Crossing Maintain RA
MVSM – Maintain Vertical Speed RA
NMAC – Near Mid-Air Collision
RA – Resolution Advisories
TA – Traffic Advisory
TCAS – Traffic Alert and Collision Avoidance System
VMD – Vertical Miss Distance

Glossary

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

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

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

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

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

References

[IATA/EUROCONTROL Guidance Material](#) on Performance assessment of pilot compliance to Traffic Alert and Collision Avoidance System (TCAS) using Flight Data Monitoring (FDM), January 2019

[EUROCONTROL ACAS Guide](#), December 2017

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