



SPR for automatic responses to ACAS RAs

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Abstract

Pilots do not very often respond to the triggered RAs exactly as expected by TCAS II and this negatively affects TCAS II safety benefits and compatibility with ATC operations. A solution to this issue would be to couple TCAS with the AutoPilot (named hereafter AutoPilot TCAS) so that the aircraft would automatically respond to the RAs instead of the current manual response performed by pilots. This extension to all TCAS-equipped aircraft of an Airbus-implemented service has been subject to a validation exercise. The current document presents safety and performance requirements for implementing such a service as derived from the validation report and RTCA relevant MOPS.

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'AP/FD TCAS' feature which has been assessed within [6] and from which part of the following requirements is derived, is patented by Airbus through the following references:

- French application number: FR20040010613
- French publication number: FR2876483
- PCT filing number: PCT/FR2005/002460
- PCT publication number: WO2006040441

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Executive summary

Since 2005, all civil turbine-engined aircraft with more than 19 passengers or weighing more than 5,700 kg flying in the European airspace are required to be equipped with TCAS II. This system has been introduced in order to reduce the risk of mid-air collisions or near mid-air collisions between aircraft as a last-resort safety net and it has demonstrated its effectiveness. However, the safety benefits provided by TCAS II and its compatibility with Air Traffic Control (ATC) operations depend on the pilots' responses to the triggered RAs and operational monitoring programmes have shown that some pilots do not follow their RAs and for those responding to the RAs, the actual reactions vary from the expected ones (e.g. too slow, too aggressive, etc.).

To address this problem, Airbus has recently developed, certified and implemented a solution that couples TCAS II to the AutoPilot for an automatic response to RAs. The service under consideration in this document is the extension of such a solution to all TCAS-equipped aircraft (not only Airbus), which fly in all operational environments. The validation exercise computed key performance indicators and checked their acceptability over a number of scenarios. It showed that several sets of parameters satisfy the acceptability criteria.

The current document presents the safety and performance requirements for this operational service, using the AutoPilot coupled to TCAS, hereafter named AutoPilot TCAS. Performance requirements are derived from two sources:

- the validation report for the validation exercise introduced above;
- the Minimal Operation Performance Standards (MOPS) for Automatic Flight Guidance and Control Systems and Equipment.

1 Introduction

1.1 Purpose of the document

This Safety and Performance Requirements (SPR) document provides the safety and performance requirements for automatic responses to TCAS RAs for all TCAS-equipped aircraft, through the coupling of TCAS and the AutoPilot. The SPR also provides the service allocation to system functions and information services.

1.2 Scope

This document supports the operational service and concept elements identified in [5] and [6]. These services are expected to be operational (IOC) in the 2011-2013 time frame.

1.3 Intended audience

This document is intended for the partners involved in the project. It is also intended to provide inputs to Projects 4.2/5.2 and 4.8.3.

No system project in charge of this service exists as the service is already implemented by a manufacturer; the current document is intended to help the extension of this service to other fleets. Therefore, it will also serve to progress on the subject with standardisation bodies, in particular EUROCAE WG75, RTCA SC-147 and RTCA SC-220.

1.4 Structure of the document

Section 1 provides a high-level introduction to the document.

Section 2 summarizes the operational concept based on the descriptions provided in [5] and [6].

Section 3 lists the safety and performance requirements for the service of automatic response to ACAS RAs.

Section 4 presents their allocation to system functions.

Appendix A presents the assessments which were performed to extract the requirements listed in Section 3.

Appendix B traces the adaptations made to requirements extracted from DO-325.

1.5 Background

Since 2005, all civil turbine-engined aircraft with more than 19 passengers or a maximum take-off mass of more than 5,700 kg flying in the European airspace are required to be equipped with TCAS II. This system has been introduced in order to reduce the risk of mid-air collisions or near mid-air collisions between aircraft as a last-resort safety net and it has demonstrated its effectiveness. However, the safety benefits provided by TCAS II and its compatibility with Air Traffic Control (ATC) operations depend on the pilots' responses to the triggered RAs.

TCAS II operational monitoring programmes have shown that pilots do not always follow their RAs thus undermining the safety enhancement brought by TCAS. Pilot non-compliance with RAs is the main factor that lowers TCAS performance. Furthermore, some studies have also shown that pilots following the RAs do not manoeuvre exactly as expected by TCAS specifications. These variations can affect TCAS II safety benefits (e.g. inefficient manoeuvre due to slow and smooth reaction) or degrade compatibility with ATC operations (e.g. unnecessary large vertical deviations due to over-reaction).

To address this problem, the proposed solution is to perform automatic responses to RAs instead of responses manually flown by pilots.

Airbus has already developed, certified and implemented a solution by linking TCAS to the Auto-Pilot (AP) for an automatic response to RAs. Airbus solution also links TCAS to the Flight Director (FD) to improve manual responses by pilots.

A validation exercise investigated the impact of linking TCAS to the Auto-Pilot (AutoPilot TCAS) for an automatic response to RAs for all TCAS-equipped aircraft and not just Airbus aircraft.

In parallel, RTCA SC-220 published Minimal Operation Performance Standards (MOPS) for Automatic Flight Guidance and Control Systems and Equipment which include an appendix with requirements on AP/FD TCAS.

1.6 Glossary of terms

NA

1.7 Acronyms and Terminology

Term	Definition
ACAS	Airborne Collision Avoidance System
AP/FD	Auto-Pilot / Flight Director
ATC	Air Traffic Control
CAS	Collision Avoidance System
MOPS	Minimum Operational Performance Standard
PF	Pilot Flying
RA	Resolution Advisory
RTCA	The US not-for-profit organization that produces standards for aviation systems, such as TCAS
SC	Sub Committee
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SJU Work Programme	The programme which addresses all activities of the SESAR Joint Undertaking Agency.
SESAR Programme	The programme which defines the Research and Development activities and Projects for the SJU.
TCAS	Traffic alert and Collision Avoidance System
WG	Working Group

2 Summary of Operational Concept (from OSED)

2.1 Description of the Concept Element

Since 2005, all civil turbine-engined aircraft with more than 19 passengers or a maximum take-off mass of more than 5,700 kg flying in the European airspace are required to be equipped with TCAS II. The safety benefits provided by TCAS II and its compatibility with Air Traffic Control (ATC) operations depend on the pilots' responses to the triggered RAs.

Currently, pilots are expected to follow the TCAS II RAs even if it is contrary to an ATC clearance. The pilot response is performed manually. Optimal response is obtained when following strictly the response characteristics modelled by TCAS II (see section A.1.4.1, Table 5). Lack of response or under-response does not achieve the safe distance between aircraft targeted by TCAS while over-response might be less compatible with ATC plans.

Despite regulations and TCAS training, pilots do not always follow their RAs and those that follow their RAs do not manoeuvre exactly as expected by TCAS specifications. To address these problems, the proposed solution is to perform automatic responses to RAs instead of responses manually flown by pilots.

2.2 Description of Operational Services

The new operational service consists in allowing automatic responses to TCAS II RAs. It relies on the coupling of the autopilot system with the TCAS system.

The principle of the solution is that, when an RA is triggered by TCAS II, the aircraft autopilot is provided with the vertical rate advised by the RA and automatically switches to an AP/FD TCAS RA mode, which remains active until TCAS declares the Clear of Conflict.

In this mode, if the AutoPilot is not engaged or is disengaged by the flight crew, FD guidance is provided to the PF based on the advised vertical rate. Note that the FD part of the service is not addressed in this document as it involves manual piloting.

While the AutoPilot is engaged, it automatically follows the RA, aiming at achieving the advised vertical rate within a time at least as short as the standard pilot does (5 s), in most cases. As a result not only the likelihood of a pilot not following its RA (lack of or opposite reaction) is reduced but also the vertical profile of the reaction is improved (no weak reaction).

A constraint on the automatic response to RAs is to avoid strong reactions so as to limit the alterations to the initial flight paths. This constraint is required in order to get pilot and controller acceptance of the service.

Several AutoPilot parameters can be adjusted in pursuit of these results. In addition to the set of parameters selected by Airbus, other sets have been tested in order to assess the impact on the performances of the various TCAS-equipped aircraft. In addition, the impact of providing, when appropriate, TCAS with the indication that the aircraft will not be able to comply with "Climb" or "Increase Climb" RAs due to performance limitations was investigated.

The AutoPilot TCAS is associated with the following operational requirement:

Identifier	REQ-04.08.02-OSED-ARRA-0001
Requirement	In all cases of TCAS RA, the AutoPilot TCAS RA mode shall bring or maintain the aircraft vertical speed out of the forbidden TCAS vertical speeds, at least as efficiently as the expected standard TCAS response, while limiting as much as possible the alterations of the flight path.

Table 1 – Operational requirements

2.3 Description of Operational Environment

The "automatic response to RAs" service is an airborne service which is independent of external ATM conditions, therefore the service can be used in all environments where TCAS aircraft fly. In particular, there is no specificity related to altitude.

3 Requirements

This section describes the performance requirements extracted through the assessments presented in Appendix A and various requirements extracted from RTCA MOPS DO-325.

The requirements have been written using Requirements and V&V Data Structures and Writing Guidelines [3]. The layout to capture requirements has been generated by using SESAR template toolbox [2]; details are provided in the user manual [4].

3.1 Automatic response to RAs

3.1.1 AutoPilot coupled to TCAS (“AutoPilot TCAS”)

3.1.1.1 Performance Requirements

The following performance requirements are extracted from the OPA presented in Appendix A. The OPA itself is consolidated from the validation report [6].

In the requirements identifier, ARRA means Automatic Response to Resolution Advisories. It serves to distinguish between the requirements for this service and those produced by project 4.8.2 for other services.

Identifier	REQ-04.08.02-SPR-ARRA-0001
Requirement	The AutoPilot TCAS RA mode shall engage when a TCAS RA occurs.
	RA occurs.

Identifier	REQ-04.08.02-SPR-ARRA-0002
Requirement	The AutoPilot TCAS shall be informed of each RA occurrence, update and termination, together with the type of the RA and either the vertical speed prescribed by the RA (if corrective) or the range of vertical speeds prohibited by the RA (if preventive).
	on the range of TCAS prohibited speeds.

Identifier	REQ-04.08.02-SPR-ARRA-0003
Requirement	The AutoPilot TCAS RA mode shall not allow its engagement to be inhibited (i.e. prevented in advance of any RA) by the flight crew <i>Note: The flight crew can still prevent the automatic response in advance by switching TCAS to TA-only mode.</i>

Identifier	REQ-04.08.02-SPR-ARRA-0004
Requirement	When the AutoPilot TCAS RA mode engages in response to an initial preventive RA, the AutoPilot TCAS RA mode shall still proceed with any altitude capture that was performed by the previous AutoPilot mode.

Identifier	REQ-04.08.02-SPR-ARRA-0005
Requirement	In response to a corrective RA prescribing a positive vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA plus 200 fpm to help flight crew monitoring of the RA response. <i>Note: Other margins may be acceptable but have not been evaluated.</i>

	Factor trials conducted by Airbus is that the RA display must show that the vertical speed needle is clearly in the green area when the AP/FD TCAS mode is following an RA. To be just at the limit could sometimes be misleading for the pilots. Therefore, Airbus decided to target a vertical speed 200 fpm greater in absolute value than the vertical speed required by the TCAS RAs except for "Level-Off" and "Maintain" RAs. The simulations have shown that this additional margin is providing additional safety benefits while not impacting the compatibility with ATC.
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Identifier	REQ-04.08.02-SPR-ARRA-0006
Requirement	In response to a corrective RA prescribing a negative vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA minus 200 fpm to help flight crew monitoring of the RA response. <i>Note: Other margins may be acceptable but have not been evaluated.</i>
	Factor trials conducted by Airbus is that the RA display must show that the vertical speed needle is clearly in the green area when the AP/FD TCAS mode is following an RA. To be just at the limit could sometimes be misleading for the pilots. Therefore, Airbus decided to target a vertical speed 200 fpm greater in absolute value than the vertical speed required by the TCAS RAs except for "Level-Off" and "Maintain" RAs.

Identifier	REQ-04.08.02-SPR-ARRA-0007
Requirement	In response to a corrective RA prescribing a null vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA (i.e. 0).
	Factor trials conducted by Airbus is that the RA display must show that the vertical speed needle is clearly in the green area when the AP/FD TCAS mode is following an RA. To be just at the limit could sometimes be misleading for the pilots. Therefore, Airbus decided to target a vertical speed 200 fpm greater in absolute value than the vertical speed required by the TCAS RAs except for "Level-Off" and "Maintain" RAs.

Identifier	REQ-04.08.02-SPR-ARRA-0008
Requirement	In response to a preventive RA that does not include the aircraft current vertical speed in its range of prohibited vertical speeds, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall
	Preventive RAs only prohibit a range of vertical speeds, which is displayed by a red area. As there is no TCAS prescribed vertical speed, there is no green area and no margin on the target vertical speed needs to be taken. The only constraint is to make sure to leave the range of prohibited speeds and stay outside of it.

Identifier	REQ-04.08.02-SPR-ARRA-0009
Requirement	<i>Note: the current aircraft vertical speed may be inside the range of prohibited speeds at the time the preventive RA is generated because TCAS RAs are based on a tracked own vertical speed.</i> In response to a preventive RA that does include the aircraft current vertical

	<p>speed in its range of prohibited vertical speeds, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft outside of the range of prohibited vertical speeds.</p> <p><i>Note: the current aircraft vertical speed may be inside the range of prohibited speeds at the time the preventive RA is generated because TCAS RAs are based on a tracked own vertical speed.</i></p>
	<p>Preventive RAs only prohibit a range of vertical speeds, which is displayed by a red area. As there is no TCAS prescribed vertical speed, there is no green area and no margin on the target vertical speed needs to be taken. The only constraint is to make sure to leave the range of prohibited speeds and stay outside of it.</p>

Identifier	REQ-04.08.02-SPR-ARRA-0010
Requirement	<p>When engaged in normal flight envelope and while it is not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft on a vertical trajectory that provides a vertical displacement at least as large as the one that would be provided by at least one of the following response modelling applied to all RAs:</p> <ul style="list-style-type: none"> • <u>a delay of no more than 3 seconds and a vertical acceleration of at least 0.15 g; or</u> • <u>a delay of no more than 4 seconds and a vertical acceleration of at least 0.20 g; or</u> • <u>a delay of no more than 5 seconds and a vertical acceleration of at least 0.30 g.</u> <p><i>Note: these response parameters are applied to all RAs (i.e. including Increase and Reverse RAs).</i></p> <p><i>Note: the values given above takes the conservative assumption of no increase in pilot response rate to RA. (When coupled to Autopilot, the crew would have to disengage the AutoPilot or select another AutoPilot mode to supersede the TCAS RA manoeuvre). Assuming a slight increase of response rate, other values such as a delay of 5 seconds and a vertical acceleration of at least 0.25 g. could become acceptable.</i></p>

Identifier	REQ-04.08.02-SPR-ARRA-0011
Requirement	<p>The AutoPilot TCAS RA mode shall remain engaged in case of vertical performance limitations leading to an under-response with respect to the TCAS expectations.</p> <p><i>Note: it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature.</i></p>

Identifier	REQ-04.08.02-SPR-ARRA-0012
Requirement	<p>If the AutoPilot TCAS provides an indication to the flight crew that the AutoPilot TCAS RA mode cannot achieve or maintain its target vertical speed due to vertical performance limitations, appropriate procedures and training requirements shall be defined to avoid improper crew response,</p>

	such as reaction opposite to the current RA.
Identifier	REQ-04.08.02-SPR-ARRA-0013
Requirement	<p>When the RA is terminated, the AutoPilot TCAS RA mode shall guide the aircraft to the selected altitude.</p> <p><i>Note: an RA is generally terminated with a “Clear of Conflict” annunciation. It can be terminated without this annunciation in some cases: when the ownship aircraft passes below 900 ft height, in case of terrain alert, windshear alert, stall warning, TA only mode selection, etc.</i></p> <p><i>Note: other solutions may be acceptable but have not been evaluated.</i></p>
]

Table 2 – Performance requirements

3.1.1.2 Requirements from DO-325 – Appendix C

In December 2010, RTCA published DO-325 “MOPS for Automatic Flight Guidance and Control Systems and Equipment”. In particular, it includes an appendix (“Appendix C: Installation guidance for Autopilot / Flight Director / Autothrust coupled to TCAS”) providing requirements and recommendations related to the AP/FD TCAS RA mode. The scope is wider than the performance assessment conducted in SESAR P4.8.2 and these requirements are also relevant to consider in this SPR.

In the requirements identifier, ARRA means Automatic Response to Resolution Advisories. It serves to distinguish between the requirements for this service and those produced by project 4.8.2 for other services.

Identifier	REQ-04.08.02-SPR-ARRA-0100
Requirement	The AutoPilot TCAS RA mode shall exhibit behaviour consistent with normal AutoPilot modes behaviour and TCAS commands and warning.
	Consistency with other AP modes and TCAS outputs
	<In Progress>
	<Functional><Interoperability>

Identifier	REQ-04.08.02-SPR-ARRA-0101
Requirement	The AutoPilot TCAS RA mode shall be distinguishable from other AutoPilot modes
	<i>Note: for example, Vertical Speed mode shall not be used as a TCAS RA mode indication if it exists as a basic AutoPilot mode indication.</i>

Identifier	REQ-04.08.02-SPR-ARRA-0102
Requirement	Except in cases where there is insufficient aircraft performance available to comply with the displayed RA while manoeuvring laterally, and when it is possible, the AutoPilot TCAS RA mode should have no effect on lateral guidance objectives.
	<i>Note: The vertical RA response is priority.</i>

Identifier	REQ-04.08.02-SPR-ARRA-0103
Requirement	Except in cases where there is insufficient aircraft performance available to comply with the displayed RA while manoeuvring laterally, and when it is possible, the AutoPilot TCAS RA mode should not lead to loss of LOC

	capture or loss of Nav mode. <i>Note: The vertical RA response is priority.</i>
Identifier	REQ-04.08.02-SPR-ARRA-0104
Requirement	All AutoPilot RA indications shall not conflict with any existing RA indications. <i>Note: The flight crew is provided with adequate means to monitor compliance to the Vertical Speed RA guidance cues while the Autopilot/Flight Director flown RA manoeuvre is conducted</i>
Identifier	REQ-04.08.02-SPR-ARRA-0105
Requirement	Since AFGCS speed protection may limit aircraft actual response in such a way that the TCAS vertical speed command will not be reached, the AutoPilot TCAS RA guidance shall consider the behavior of speed envelope protection during TCAS guidance including associated alerts.
Identifier	REQ-04.08.02-SPR-ARRA-0106
Requirement	When a TCAS “Clear of conflict” is generated following a corrective RA, the AutoPilot TCAS RA mode behaviour shall be predictable.
Identifier	REQ-04.08.02-SPR-ARRA-0107
Requirement	When a Resolution Advisory is aborted without “Clear of conflict”, the AutoPilot TCAS RA mode behaviour shall be predictable.
	Predictability of behaviour after RA abortion
Identifier	REQ-04.08.02-SPR-ARRA-0108
Requirement	The AutoPilot TCAS RA mode shall allow manual disengagement (i.e. flight crew interruption of automatic response to an ongoing RA).
Identifier	REQ-04.08.02-SPR-ARRA-0109
Requirement	The AutoPilot TCAS RA guidance shall not induce automatic autopilot disengagement when initiated in the normal flight envelope.
Identifier	REQ-04.08.02-SPR-ARRA-0110
Requirement	If the AutoPilot TCAS RA mode availability is lost while the AutoPilot TCAS RA mode is engaged, the AutoPilot TCAS shall alert the flight crew so that flight crew can take appropriate actions
Identifier	REQ-04.08.02-SPR-ARRA-0111
Requirement	If the AutoPilot TCAS RA mode availability is lost before the AutoPilot TCAS RA mode is engaged, the Autopilot TCAS shall provide an obvious indication to the flight crew.
Identifier	REQ-04.08.02-SPR-ARRA-0112
Requirement	AutoPilot TCAS RA mode shall interact compatibly with Autothrust modes and engagement status.
Identifier	REQ-04.08.02-SPR-ARRA-0113
Requirement	RA displays provided by AutoPilot TCAS shall comply with the requirements in ED-143/DO-185B. <i>Note: ED-143/DO-185B., §2.2.6.2, RA Displays specifies requirements for the following TCAS RA display:</i> <ul style="list-style-type: none"> §2.2.6.2.2 RA/Vertical Speed Indicator (VSI) (Round Dial); §2.2.6.2.3 RA/VSI (Integrated Tape VSI on a Primary Flight Display (PFD)); §2.2.6.2.4 Pitch Cues on a PFD;

	§2.2.6.2.5 <i>Flight Director Guidance</i> ; §2.2.6.2.6 <i>Head-up display / Flight Path target.</i>
	<HMI>

Table 3 –Requirements from DO-325 Appendix C

4 Traceability matrix

The following traceability matrix cannot be filled completely due to lack of data on the possible values of the fields of three columns.

Requirement Identification	Requirement title	Functional block Id < xxxxx >	System Function Identifier	Information Service or Application Service Identifier
REQ-04.08.02-SPR-ARRA-0001	Engagement conditions			
REQ-04.08.02-SPR-ARRA-0002	Knowledge of essential RA information			
REQ-04.08.02-SPR-ARRA-0003	Forbidden inhibition			
REQ-04.08.02-SPR-ARRA-0004	Preservation of ongoing altitude capture			
REQ-04.08.02-SPR-ARRA-0005	Target vertical speed for corrective RAs (1)			
REQ-04.08.02-SPR-ARRA-0006	Target vertical speed for corrective RAs (2)			
REQ-04.08.02-SPR-ARRA-0007	Target vertical speed for corrective RAs (3)			
REQ-04.08.02-SPR-ARRA-0008	Target vertical speed for preventive RAs (1)			
REQ-04.08.02-SPR-ARRA-0009	Target vertical speed for preventive RAs (2)			
REQ-04.08.02-SPR-ARRA-0010	Minimum vertical profile performance			
REQ-04.08.02-SPR-ARRA-0011	No influence of vertical performance limitations			
REQ-04.08.02-SPR-ARRA-0012	Use of indications of partial RA compliance			
REQ-04.08.02-SPR-ARRA-0013	Reaction after RA termination			
REQ-04.08.02-SPR-ARRA-0101	Consistency with other AP modes and TCAS outputs			

Requirement Identification	Requirement title	Functional block Id < xxxxx >	System Function Identifier	Information Service or Application Service Identifier
REQ-04.08.02-SPR-ARRA-0102	Distinction from other AP modes			
REQ-04.08.02-SPR-ARRA-0103	Minimal interaction with lateral guidance objectives			
REQ-04.08.02-SPR-ARRA-0103	Minimal interaction with LOC capture and Nav mode			
REQ-04.08.02-SPR-ARRA-0104	Consistency between RA indications			
REQ-04.08.02-SPR-ARRA-0105	Consideration of speed envelope protection	TBD	TBD	TBD
REQ-04.08.02-SPR-ARRA-0106	Predictability of behaviour after CoC			
REQ-04.08.02-SPR-ARRA-0107	Predictability of behaviour after RA abortion			
REQ-04.08.02-SPR-ARRA-0108	Manual disengagement of TCAS RA mode			
REQ-04.08.02-SPR-ARRA-0109	Minimal autopilot disengagement			
REQ-04.08.02-SPR-ARRA-0110	Alert of loss of TCAS RA mode			
REQ-04.08.02-SPR-ARRA-0111	Indication of loss of TCAS RA mode			
REQ-04.08.02-SPR-ARRA-0112	Compatibility with Autothrust modes and engagement status			
REQ-04.08.02-SPR-ARRA-0113	Compliance of RA displays with ED-143/DO-185B			

Table 4 – Requirement traceability matrix

5 References and Applicable Documents

5.1 Applicable Documents

This SPR complies with the requirements set out in the following documents:

- [1] SESAR SEMP 2.0
- [2] Template Toolbox 02.00.00
- [3] Requirements and V&V Guidelines 02.00.00
- [4] Toolbox User Manual 02.00.00

5.2 Reference Documents

The following documents were used to provide input / guidance / further information / other:

- [5] 4.8.2 - Validation plan for automatic responses to ACAS RA – D05 – Edition 00.01.00 – 17 September 2010
- [6] 4.8.2 - Validation report for automatic responses to ACAS RA - D06 - Edition 00.01.00 - 26 April 2011
- [7] RTCA SC-220 - Minimal Operation Performance Standards (MOPS) for Automatic Flight Guidance and Control Systems and Equipment – DO-325 – Edition 1 – 08 December 2010

Appendix A Assessment / Justifications

A.1 Safety and performance assessment

A.1.1 Assumptions

Assumption: Only the AutoPilot guidance is assessed in the OPA. The use of the Flight Director guidance should improve the manual responses to Resolution Advisories but this was not assessed in P4.8.2.

Assumption: The AutoPilot TCAS meets the performance and functional requirements of CS 25-1329 + AMC 25-1329.

Assumption: The validation of several AutoPilot TCAS implementations was performed with TCAS II logic version 7.1. The behaviour of these implementations was not assessed with other CAS logic versions. AutoPilot TCAS is therefore assumed to be used with TCAS II logic version 7.1.

Assumption: The aircraft using the AutoPilot TCAS are equipped with an autothrust.

Assumption: AutoPilot TCAS RA mode provides an automatic TCAS guidance. Manual engagement of the AutoPilot TCAS RA mode is out of the scope of this document.

Assumption: For the purpose of the study, the proportion of flight crew deciding to not follow their RA is the same with the AutoPilot TCAS than it is without. This is a conservative assumption because not following the RA implies an active action (disengaging the AutoPilot or at least the automatic response mode) with the new operations while it only requires doing nothing with the current operations. More relaxed performance requirements on the vertical trajectory would be possible, depending on the demonstrable level of additional compliance.

A.1.2 Applicability conditions

AutoPilot TCAS RA mode is a new autopilot mode. Therefore, in order to allow the automatic response to the RA, the autopilot must be engaged when an RA occurs.

Requirement 1) The AutoPilot TCAS RA mode shall engage when a TCAS RA occurs.

AutoPilot TCAS has to react each time an RA is triggered, updated and terminated. It reacts differently to a preventive and to a corrective RA. The AutoPilot TCAS target vertical speed depends on the TCAS prescribed vertical speed or on the range of TCAS prohibited speeds.

Requirement 2) The AutoPilot TCAS shall be informed of each RA occurrence, update and termination, together with the type of the RA and either the vertical speed prescribed by the RA (if corrective) or the range of vertical speeds prohibited by the RA (if preventive).

Inhibiting the automatic response to RA could lead to flight crews not following the RA while staying in TA/RA mode. TCAS operational monitoring as well as simulations have shown that it is safer to switch to TA-only mode rather than stay in TA/RA mode when one does not want to follow the RA, because of a potential coordinated RA with the threat aircraft.

Requirement 3) The AutoPilot TCAS RA mode shall not allow its engagement to be inhibited (i.e. prevented in advance of any RA) by the flight crew

Note: The flight crew can still prevent the automatic response in advance by switching TCAS to TA-only mode.

A.1.3 Reaction to initial preventive RAs

Initial preventive RAs do not require a change in vertical speed. If the AutoPilot TCAS flew the aircraft with only the current speed as vertical speed target, there would be a risk of overshooting the altitude that was possibly targeted by the previous AutoPilot mode. So, it is necessary to take this altitude into account when performing the automatic response.

Requirement 4) When the AutoPilot TCAS RA mode engages in response to an initial preventive RA, the AutoPilot TCAS RA mode **shall** still proceed with any altitude capture that was performed by the previous AutoPilot mode.

A.1.4 Reaction to other RAs

A.1.4.1 Introduction

The reaction to RAs is defined by three parameters:

- Response time, which is the time to start to manoeuvre in response to the RA;
- Vertical acceleration at which the vertical speed required by the triggered RA is achieved; and
- Vertical speed flown in response to the RA.

The following table lists the parameters as expected by TCAS II.

Pilot model parameters	Standard values
Initial corrective RA delay	5 s
Other RA delay ¹ (1)	2.5 s
Standard RA acceleration ² (2)	0.25 g
Increase/Reversal RA acceleration	0.35 g
Climb/Descend RA rate	1500 fpm
Increase RA rate	2500 fpm
Level-Off RA rate ³ (3)	0 fpm

Table 5 – Standard pilot response parameters

The objective of the Operational Performance Assessment is to define the minimum requirements for the RA reaction parameters. To determine them, a detailed list of key performance indicators has been defined and assessed in the validation activity. The most important ones are summarised in this appendix:

- Risk ratio;
- Collision rate by flight hours;
- Vertical Miss Distances,
- Number of reversal RAs;
- Number of crossing RAs;
- Deviations;
- Complex sequence of RAs.

For a detailed description of the validation results and information about the other key performance indicators, please refer to [6].

A.1.4.2 Vertical speed

One of the results of Human Factor trials conducted by Airbus is that the RA display must show that the vertical speed needle is clearly in the green area when the AP/FD TCAS mode is following an RA. To be just at the limit could sometimes be misleading for the pilots. Therefore, Airbus decided to target a vertical speed 200 fpm greater in absolute value than the vertical speed required by the TCAS RAs except for “Level-Off” and “Maintain” RAs.

¹ Other RAs include weakening, strengthening, increase and reverse RAs

² Applicable to all RAs except Increase and Reversal RAs.

³ In TCAS II version 7.1, the “Level-Off” RA replaces the former “Adjust Vertical Speed” RAs.

The simulations have shown that this additional margin is providing additional safety benefits while not impacting the compatibility with ATC.

Requirement 5) In response to a corrective RA prescribing a positive vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA plus 200 fpm to help flight crew monitoring of the RA response.

Requirement 6) In response to a corrective RA prescribing a negative vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA minus 200 fpm to help flight crew monitoring of the RA response.

Requirement 7) In response to a corrective RA prescribing a null vertical speed, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft towards a target vertical speed equal to the vertical speed prescribed by the current RA (i.e. 0).

Note: Other margins may be acceptable but have not been evaluated.

Preventive RAs only prohibit a range of vertical speeds, which is displayed by a red area. As there is no TCAS prescribed vertical speed, there is no green area and no margin on the target vertical speed needs to be taken. The only constraint is to make sure to leave the range of prohibited speeds and stay outside of it.

Requirement 8) In response to a preventive RA that does not include the aircraft current vertical speed in its range of prohibited vertical speeds, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall maintain the current vertical speed.

Note: the current aircraft vertical speed may be inside the range of prohibited speeds at the time the preventive RA is generated because TCAS RAs are based on a tracked own vertical speed.

Requirement 9) In response to a preventive RA that does include the aircraft current vertical speed in its range of prohibited vertical speeds, when engaged in normal flight envelope and while not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft outside of the range of prohibited vertical speeds.

A.1.4.3 Vertical acceleration and delay

Only one value for the vertical acceleration and the delay has been used for all the RAs in the validation activities, e.g. the same vertical acceleration for Standard and Increase/Reverse RAs.

The assessed vertical accelerations were 0.15, 0.20, 0.25 and 0.30 g and the delays were 3, 4, 5 and 7 seconds.

In order to identify the sets of parameters that are satisfactory for setting up a performance requirement, their effect on the main performance indicators is compared to the reference value for each indicator.

In the following results, partial equipage indicates a scenario where only 50% of the all the aircraft are equipped with AutoPilot TCAS and partial compliance indicates a scenario where 20% of the flight crews decide to disengage the AutoPilot TCAS RA mode and do not follow the RA at all. Flight crews onboard unequipped aircraft were simulated to follow the RAs manually, either as expected by TCAS (standard pilot, cf. A.1.4.1) or with a range of reactions as observed in real operations (typical pilot).

As the scenarios with standard pilot always provide more constraining results, the results with typical pilots do not have an influence on the requirements and are not shown hereafter.

Risk ratio

The table shows the risk ratio (number of NMAC situations when simulating TCAS divided by the number of NMAC situations when not simulating TCAS) for the tested sets of parameters. The reference value (no AutoPilot TCAS equipped aircraft) is in the first line. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

Standard pilot		32.3							
AP/FD		Partial compliance				Full compliance			
		7s	5s	4s	3s	7s	5s	4s	3s
Partial equipage	0.15g	-	-	-	32.0	-	-	-	23.3
	0.20g	36.6	32.9	31.8	31.5	28.7	23.8	22.4	22.3
	0.25g	35.1	32.0	31.5	31.1	27.0	22.6	22.0	21.5
	0.30g	34.8	31.7	31.4	30.9	26.3	22.2	21.8	21.2
Full equipage	0.15g	-	-	-	32.0	-	-	-	14.5
	0.20g	40.8	34.6	31.6	31.0	26.0	17.6	13.8	12.8
	0.25g	38.6	33.0	30.9	30.3	22.9	15.5	12.5	11.6
	0.30g	37.3	32.2	30.7	30.0	21.1	14.5	12.3	11.1

Table 6 – Risk ratio values per set of parameters

The reference value is in the first line.

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.3 g

With a delay of 5 seconds, an acceleration of 0.25 g slightly decreases the safety benefits provided by TCAS with a standard pilot in one scenario: full equipage and partial compliance (33.0 vs. 32.3). This is due to the fact that these acceleration and delay are applied to all RAs, including those requiring a quicker response and a greater acceleration.

Collision rate by flight hours

The figure presents the variation (in percentage of the reference value) of the frequency of collision rates for the tested sets of parameters. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

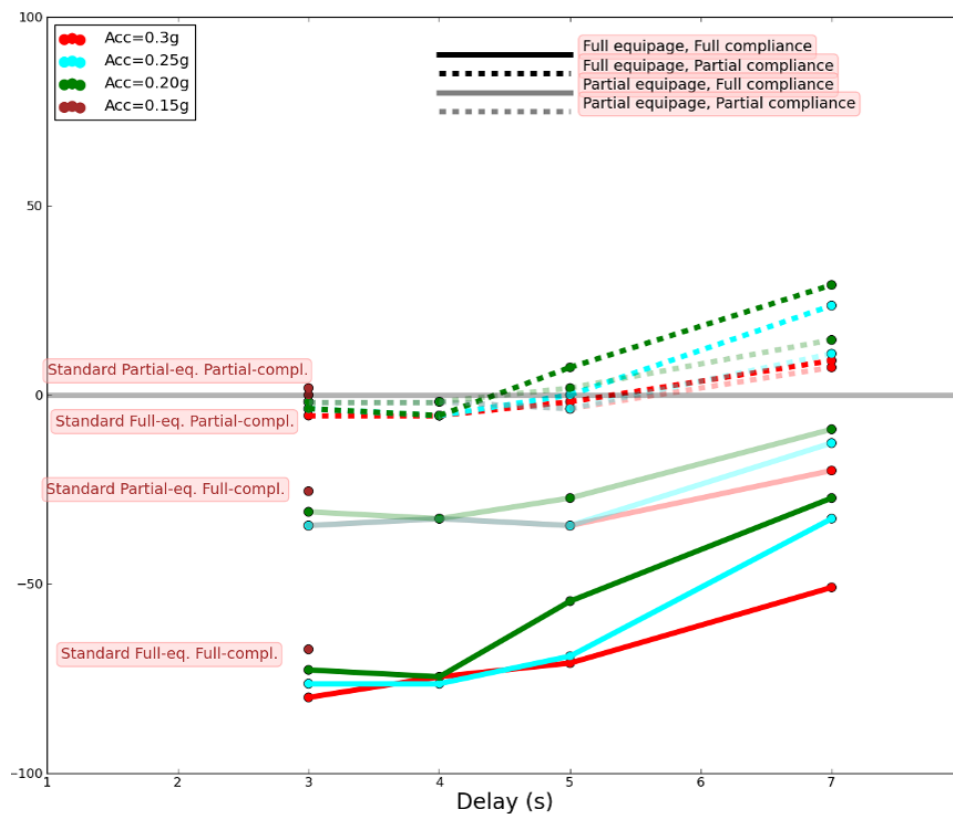


Figure 1 – Variation of the collision rate by flight hours per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.3 g

Vertical Miss Distances

The figure presents the variation (in percentage of the reference value) of the vertical miss distance between the two involved aircraft. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values greater than the reference value indicate that AutoPilot TCAS provides an improvement.

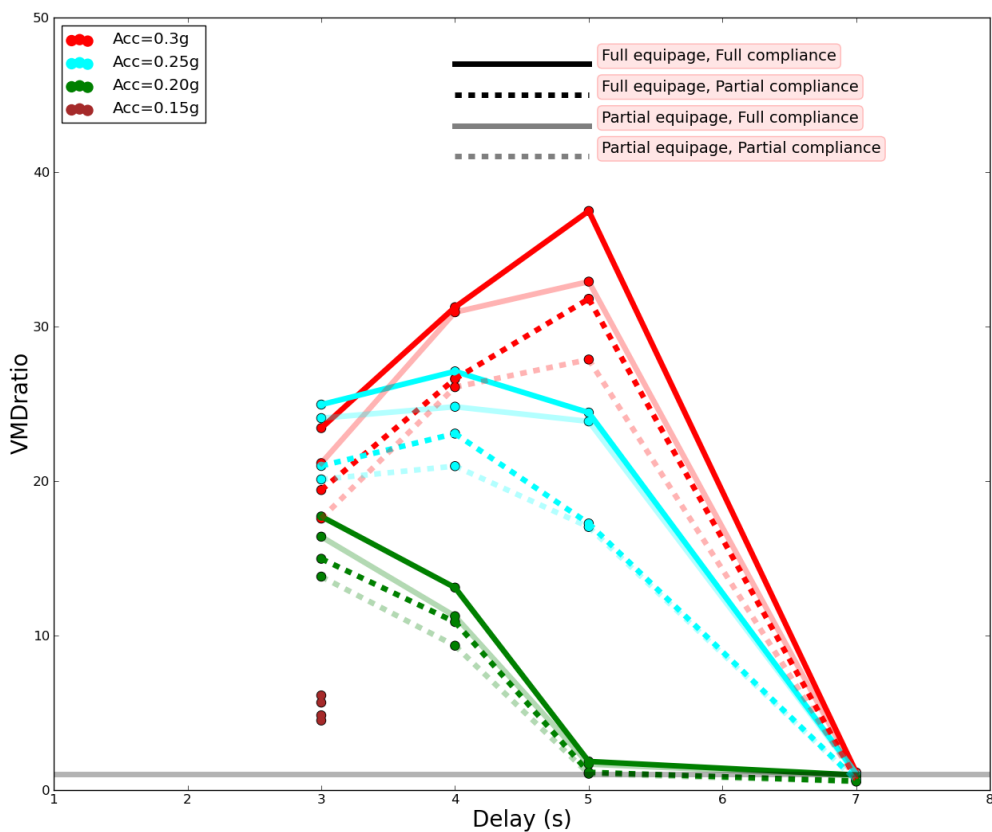


Figure 2 – Variation of vertical miss distances per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.2 g

Increase RAs

The figure presents the variation (in percentage of the reference value) of the number of increase RAs. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

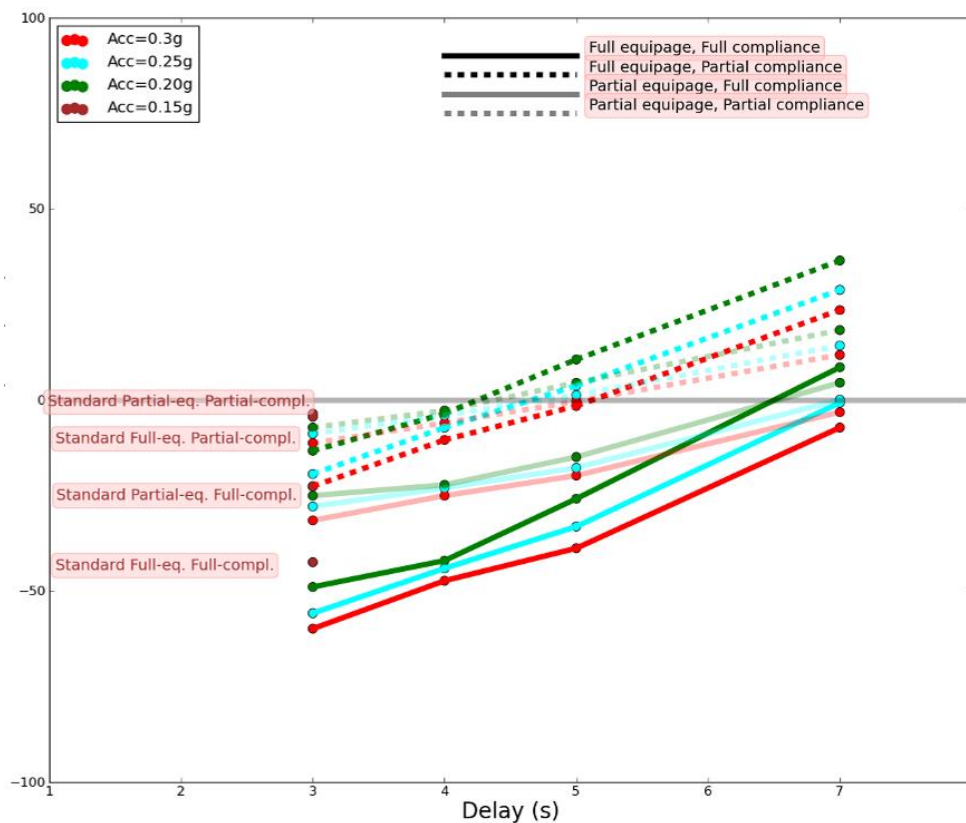


Figure 3 – Variation of increase RAs per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.3 g

Reversal RAs

The figure presents the variation (in percentage of the reference value) of the number of reversal RAs. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

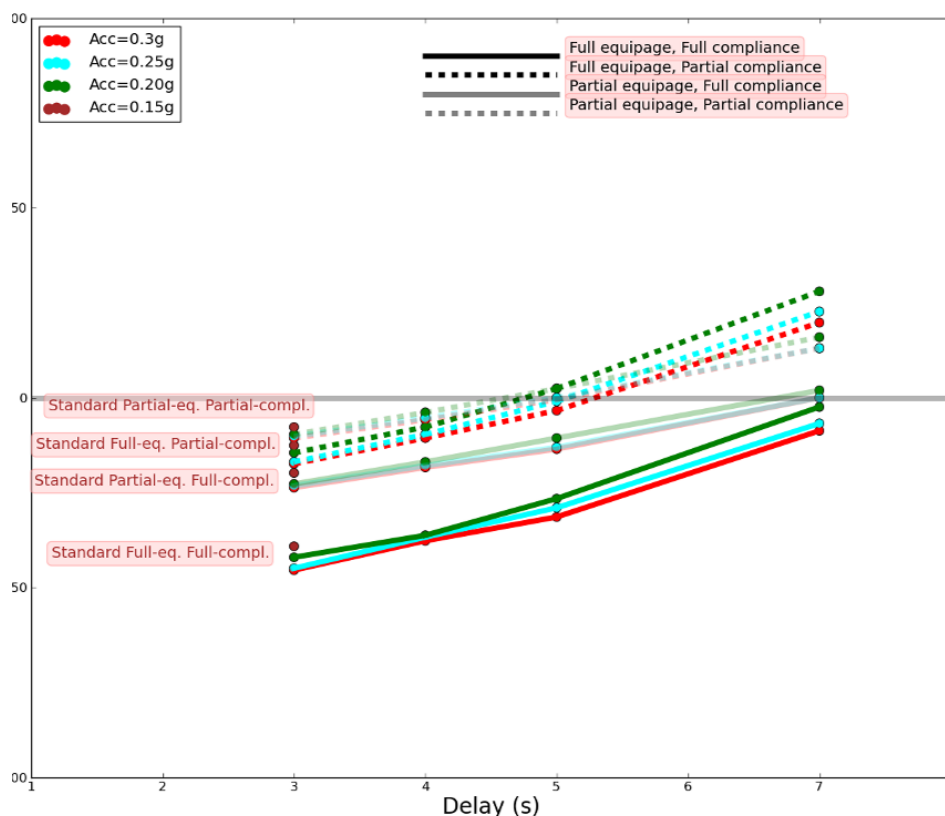


Figure 4 – Variation of reversal RAs per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.25 g

Crossing RAs

The figure presents the variation (in percentage of the reference value) of the number of crossing RAs. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

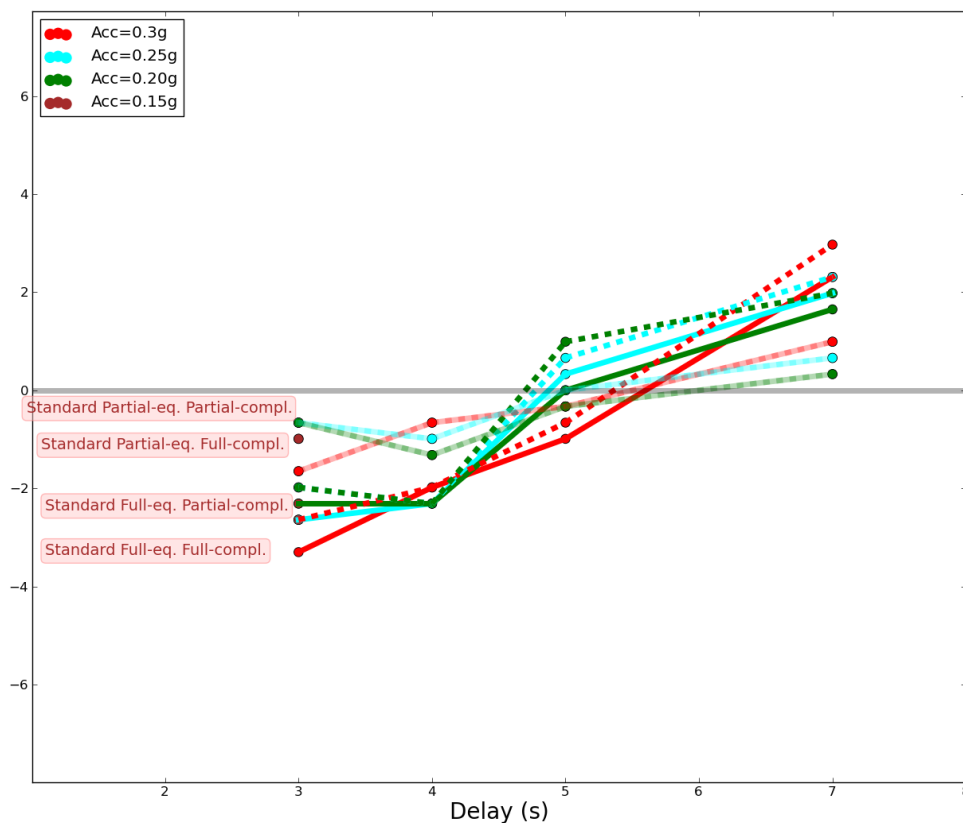


Figure 5 – Variation of crossing RAs per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.3 g

Deviations

This indicator is not a discriminating item for the sets of parameters.

Complex sequence of RAs

The figure presents the variation (in percentage of the reference value) of the number of complex sequences of RAs. The reference value (no AutoPilot TCAS equipped aircraft) is represented by the grey horizontal line at 0%. Values lower than the reference value indicate that AutoPilot TCAS provides an improvement.

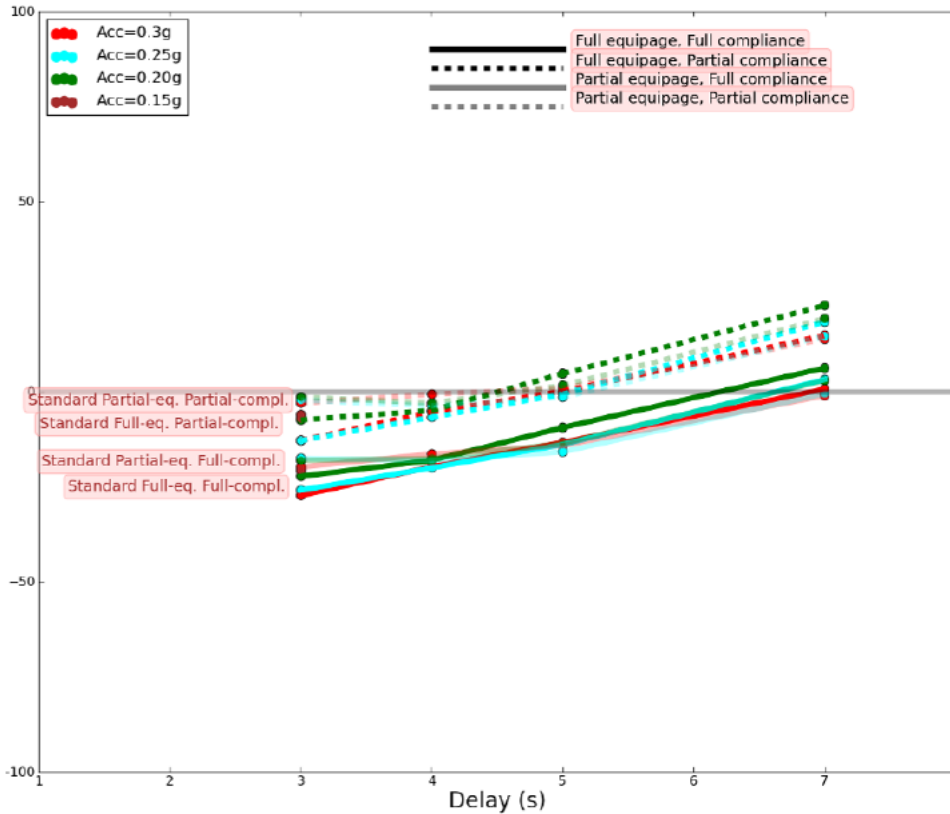


Figure 6 – Variation of complex sequences of RAs per set of parameters

There is an improvement in all scenarios for:

- delay = 3 seconds and acceleration at least 0.15 g
- delay = 4 seconds and acceleration at least 0.2 g
- delay = 5 seconds and acceleration at least 0.25 g

Synthesis

The following table summarises the results presented for each indicator. It shows which pairs of delay/acceleration provide improvements to all these indicators for all scenarios (i.e. partial/full equipage and partial/full compliance).

		Delay			
		7s	5s	4s	3s
Acceleration	0.15g	-	-	-	OK
	0.20g	No	No	OK	OK
	0.25g	No	No (*)	OK	OK
	0.30g	No	OK	OK	OK

Table 7 – Acceptable sets of parameters for the simulated response

(*): A reaction with a delay of 5 seconds and an acceleration of 0.25 g (which is the standard reaction to initial corrective RAs) improves all indicators in case of full compliance to RAs. However, in case of partial compliance to RAs like in current operations, this reaction slightly degrades some indicators. The main explanation is that these delay and acceleration are also applied to the subsequent RAs requiring a smaller delay (2.5 s) and a stronger acceleration (0.35 g).

Requirements

There is a major difference in the actual response to an RA performed by an aircraft (manually or automatically) and the simulations. Indeed, while the targeted vertical acceleration is instantaneously simulated (e.g. jump from 0 g to 0.25 g in one second), the actual vertical acceleration increases progressively towards the targeted acceleration (i.e. it takes several seconds to reach it). Furthermore, the coupling of TCAS to the auto-pilot allows for an immediate response (i.e. delay = 0 second). As a summary, the actual vertical trajectory resulting from a reaction to an RA (even when performed manually) is different from the simulated one.

The following figures showing a standard TCAS response to a “Climb” RA (after 5 seconds, with an acceleration of 0.25 g) generated at T=1 and an actual response with a progressive acceleration (0.03g/s) without any delay (like with the AutoPilot TCAS RA mode) illustrate this difference (in this example, the vertical speed is 1500 fpm for both responses).

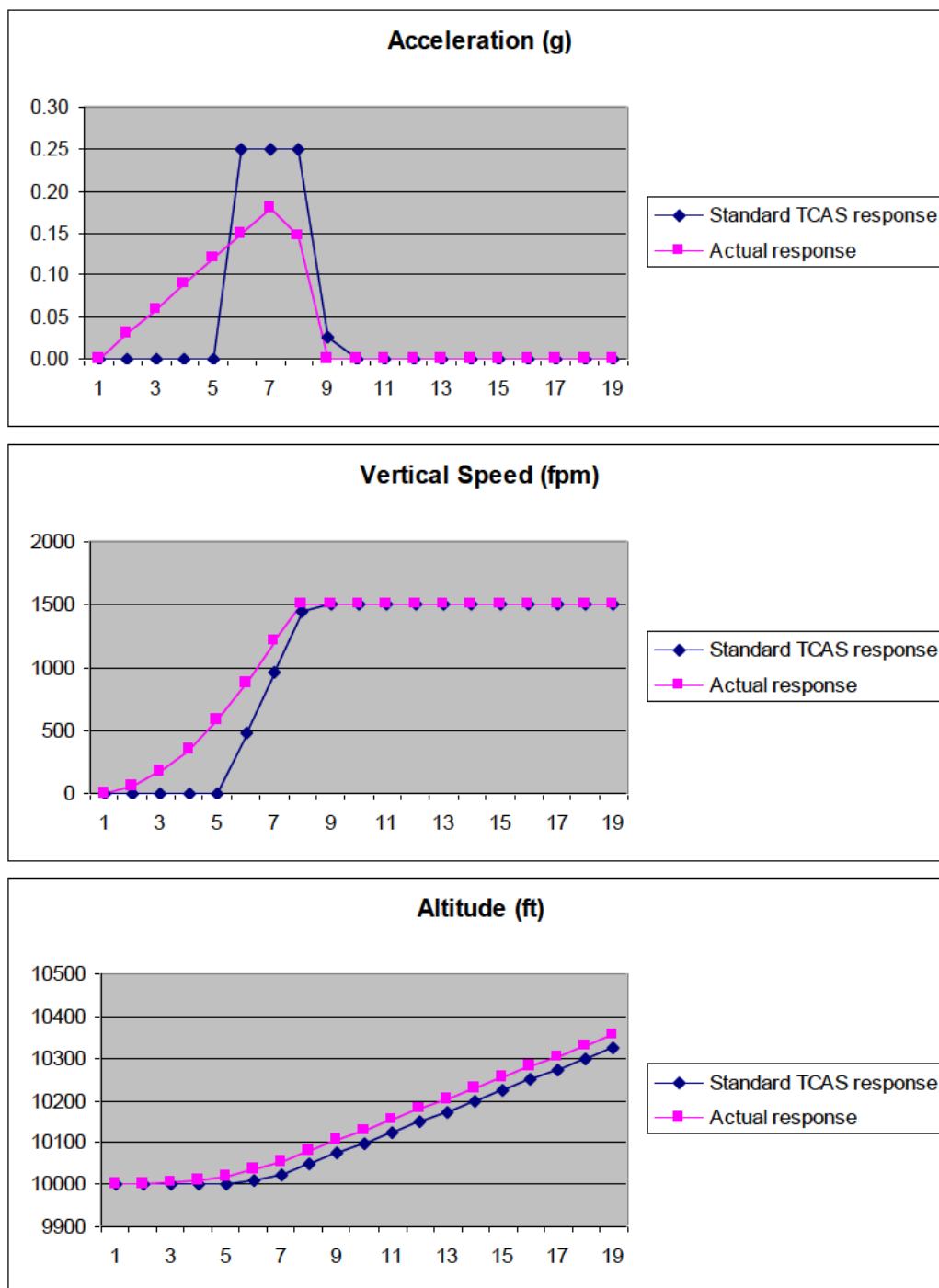


Figure 7 – Difference between simulated responses and actual responses

The main objective is that the resulting vertical trajectory with the AutoPilot TCAS RA mode is above the vertical trajectory resulting from the standard TCAS response. The other objective is that it is not too much above, which could result in operational issue (e.g. large deviations) or safety issues (e.g. induced conflicts). This was addressed by the definition of a full range of validation (performance) objectives.

As a result, the following requirement ensures a safe and efficient response to the RAs by the AutoPilot TCAS RA mode.

Requirement 10) When engaged in normal flight envelope and while it is not limited by speed protection (if any), the AutoPilot TCAS RA mode shall fly the aircraft on a vertical trajectory that

provides a vertical displacement at least as large as the one that would be provided by at least one of the following response modelling applied to all RAs:

- a delay of no more than 3 seconds and a vertical acceleration of at least 0.15 g; or
- a delay of no more than 4 seconds and a vertical acceleration of at least 0.20 g; or
- a delay of no more than 5 seconds and a vertical acceleration of at least 0.30 g.

Note: these response parameters are applied to all RAs (i.e. including Increase and Reverse RAs).

Note: the values given above takes the conservative assumption of no increase in pilot response rate to RA. (When coupled to AutoPilot, the crew would have to disengage the AutoPilot or select and other AutoPilot mode to supersede the TCAS RA manoeuvre). Assuming a slight increase of response rate, other values such as a delay of 5 seconds and a vertical acceleration of at least 0.25 g. could become acceptable.

The following figures shows, for a “Climb” RA followed by an “Increase Climb” RA:

- a simulated response at 4 seconds, 0.20 g and 200 fpm above the required vertical speed as specified in the requirement;
- a possible AutoPilot TCAS RA mode response without delay, a progressive acceleration of 0.30 g/s and 200 fpm above the required vertical speed complying with the requirement.

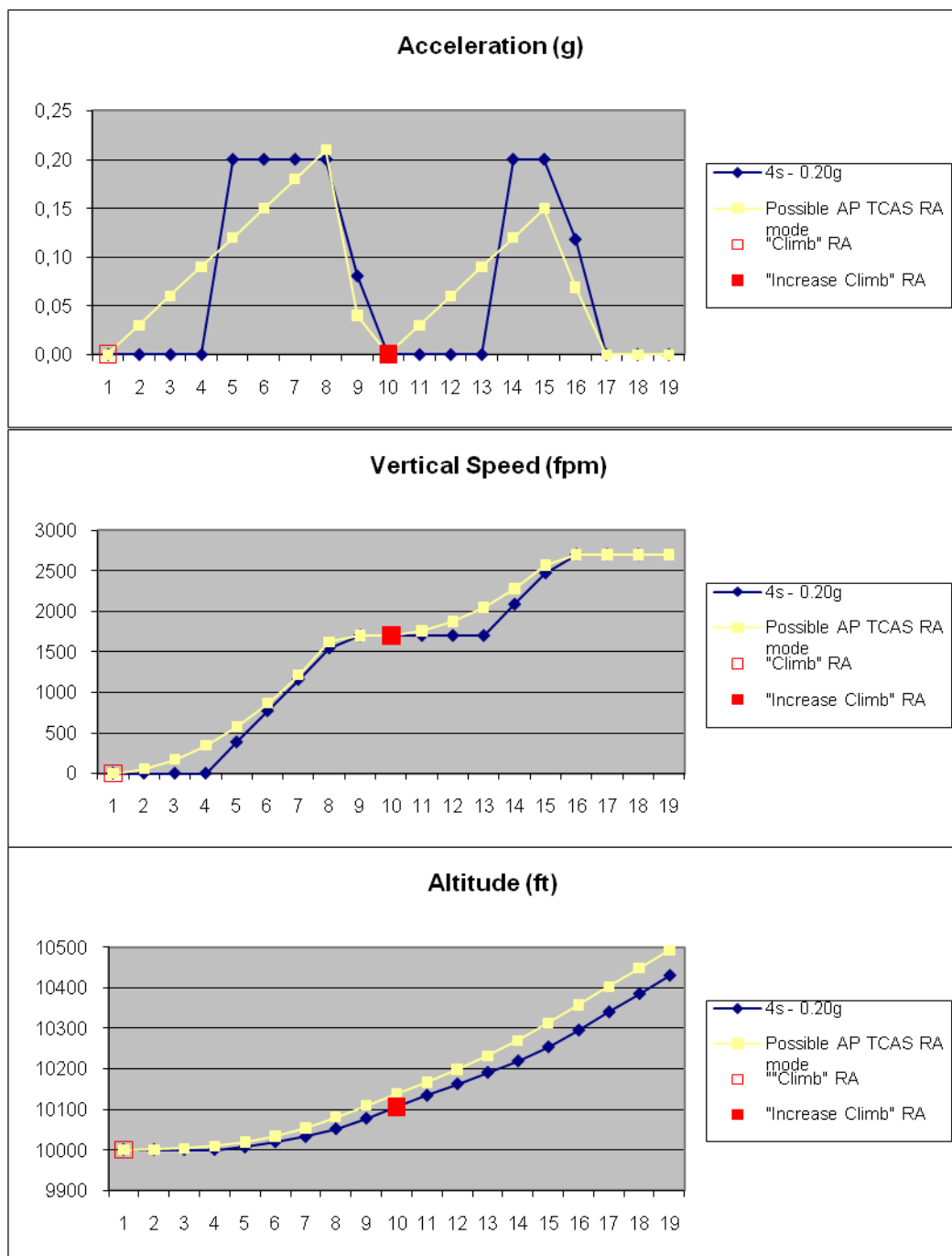


Figure 8 – Effectiveness of a possible AutoPilot TCAS RA mode response

The figure shows that even if the vertical acceleration is lower than the required one, it is compensated by the lack of delay for the reaction to the RAs and the resulting vertical trajectory with the possible AutoPilot TCAS RA mode complies with the requirement (i.e. above the trajectory obtained with a delay of 4 seconds and a vertical acceleration of at least 0.20 g).

A.1.5 Vertical performance limitations

In rare occasions, due to aircraft performance limitations, it might be not possible to reach the vertical rate prescribed by TCAS and maintain it as long as the RA is active. It was observed through the investigation of several operationally realistic situations that it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature. Additionally this study found that climb inhibitions are not properly handled in the CAS logic, and should therefore be avoided as much as possible.

Requirement 11) The AutoPilot TCAS RA mode shall remain engaged in case of vertical performance limitations leading to an under-response with respect to the TCAS expectations.

Note: it is preferable to perform a manoeuvre even with a vertical rate lower than that expected by TCAS rather than using the existing RA climb inhibition feature.

Indications to the flight crew that the AutoPilot TCAS RA mode cannot achieve or maintain its target vertical speed can be a source of confusion for the flight crew. The goal of such indications is to keep the flight crew from wondering why the RA is only partially followed and to reassure them that the system took the best course of action considering the situation. However, without proper procedures and training, the flight crew might decide that the automatic response is not satisfactory and might fly the aircraft manually in a sense opposite to the RA.

Requirement 12) If the AutoPilot TCAS provides an indication to the flight crew that the AutoPilot TCAS RA mode cannot achieve or maintain its target vertical speed due to vertical performance limitations, appropriate procedures and training requirements shall be defined to avoid improper crew response, such as reaction opposite to the current RA.

A.1.6 Reaction after RA termination

In operations, the ICAO ACAS procedure includes not only the response to the RAs themselves, but also the return to the previous clearance. The AutoPilot TCAS was validated including such a feature, which aims at minimizing the deviation from ATC clearances. This feature is also mentioned as a possibility in section C.2.1 k of DO-325 [7]

Requirement 13) When the RA is terminated, the AutoPilot TCAS RA mode shall guide the aircraft to the selected altitude.

Note: an RA is generally terminated with a "Clear of Conflict" annunciation. It can be terminated without this annunciation in some cases: when the ownship aircraft passes below 900 ft height, in case of terrain alert, windshear alert, stall warning, TA only mode selection, etc.

Note: other solutions may be acceptable but have not been evaluated.

Appendix B Record of DO-325 adaptations for this SPR

The following table presents all requirements on AP/FD TCAS introduced in [7], tells if the requirement was kept or changed for the SPR and explains the reason of any change.

Ref in DO	Status in SPR	Ref in SPR	Change details
C.2.1 a	left out	n/a	It is an assumption of the SPR.
C.2.1 b	left out	n/a	The need for revised TCAS procedures is not a requirement on the system itself
C.2.1 c	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0100	More correct phrasing for a requirement. 'expected behaviour' is too lax. FD is out of scope of the SPR
C.2.1 d	rephrased, clarified, rescoped and changed into a requirement	REQ-04.08.02-SPR-ARRA-0101	Example put in a note 'distinguished' does not clearly convey that the requirement is on the HMI FD is out of scope of the SPR
C.2.1 e.1	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0102	Reason of restriction put in a note. FD is out of scope of the SPR
C.2.1 e.2	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0103	Reason of restriction put in a note. FD is out of scope of the SPR
C.2.1 f	left out	n/a	Requirement to engage only on TCAS RA included in another section of the SPR
C.2.1 g	rescoped	REQ-04.08.02-SPR-ARRA-0104	FD is out of scope of the SPR
C.2.1 h	left out	n/a	More precise requirement derived from the VR and included in another section of the SPR
C.2.1 h	left out	n/a	More precise requirement derived from the VR and included in another section of the SPR
C.2.1 i	rescoped	REQ-04.08.02-SPR-ARRA-0105	FD is out of scope of the SPR
C.2.1 j	left out	n/a	Requirement on TCAS which is not needed for this SPR as another requirement tells that RA should be followed even if the target vertical speed cannot be reached or maintained until the CoC.
C.2.1 k	left out	n/a	Not a real requirement. The need is taken into account by a requirement to return to selected SFL included in another section of the SPR
C.2.1 k	left out	n/a	Requirement to return to selected SFL included in another section of the SPR
C.2.1 k	rescoped	REQ-04.08.02-SPR-ARRA-0106	FD is out of scope of the SPR
C.2.1 l	left out	n/a	Not a real requirement. The need is taken into account by a requirement to return to selected SFL included in another section of the SPR
C.2.1 l	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0107	Condition put first FD is out of scope of the SPR
C.2.1 m.1	left out	n/a	Requirement not seen as desirable. Requirement forbidding the inhibition included in another section of the SPR
C.2.1 m.2	left out	n/a	Irrelevant as inhibition is forbidden by the SPR
C.2.1 m.3	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0108	More correct phrasing for a requirement. Note removed as it is a recommendation on the validation/verification of the requirement. FD is out of scope of the SPR
C.2.1 n	changed into a requirement	REQ-04.08.02-SPR-ARRA-0109	

Ref in DO	Status in SPR	Ref in SPR	Change details
C.2.1 o.1	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0110	More correct phrasing for a requirement. FD is out of scope of the SPR
C.2.1 o.2	rephrased and rescoped	REQ-04.08.02-SPR-ARRA-0111	More correct phrasing for a requirement. FD is out of scope of the SPR "unless..." was removed because an assumption of the study is that there is no manual engagement of the system.
C.2.1 p	left out	n/a	FD is out of scope of the SPR
C.2.1 q	left out	n/a	Not a real requirement. It is just a reminder that new failure modes may appear and that proper reactions should be defined.
C.2.1 q	left out	n/a	Not a real requirement. It is just a reminder that new failure modes should be studied during system development.
C.2.2	rescoped	REQ-04.08.02-SPR-ARRA-0112	FD is out of scope of the SPR
C.2.3 intro	rephrased, rescoped and changed into a requirement	REQ-04.08.02-SPR-ARRA-0113	More correct phrasing for a requirement. All RA displays are in scope, not only pitch cues.
C.2.3 a	left out	n/a	FD is out of scope of the SPR
C.2.3 b	left out	n/a	FD is out of scope of the SPR Overlap with C.2.1 g

Table 8 – List of adaptations to DO-325 requirements

-END OF DOCUMENT -