



Minimum Aviation System Performance Standards (MASPS) for the Interoperability of Airborne Collision Avoidance Systems (CAS)

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FOREWORD

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CHAPTER 1

PURPOSE AND SCOPE

1.1 INTRODUCTION

This document presents high level requirements (i.e. Minimum Aviation System Performance Standards (MASPS)) for the interoperability of airborne Collision Avoidance Systems (CAS). Its main objective is to ensure that new CAS do not degrade the operation of existing CAS. It specifies system characteristics that should be useful to designers, manufacturers, installers and users of the equipment. When some requirements cannot be fully defined, explanatory text is included to describe the basis on which requirements are to be developed.

Compliance with these MASPS does not ensure that the equipment will be approved for operation. These MASPS do not address the functionality or performance of CAS beyond the requirement of interoperability between CAS. Minimum Operational Performance Standards (MOPS) address safety and operational suitability performance criteria. Any MOPS that are developed for a future CAS should use these MASPS as guidance for its interoperability with existing CAS. Regulatory application of this document is the sole responsibility of the appropriate regulatory authority.

This document considers equipment configurations consisting of a CAS with an Automatic Dependent Surveillance-Broadcast (ADS-B) transmitter/receiver, with or without a Mode S transponder and with or without a 1030 MHz transmitter.

The word “equipment” as used in this document includes all components and units necessary for the system to properly perform its intended function. For example, the equipment may include a Traffic Alert and Collision Avoidance System (TCAS¹) unit coupled to a Mode S transponder. In this example, all the foregoing components and units comprise the equipment. It should not be inferred from this example that each CAS design will necessarily include all the foregoing components or units. This will depend on the specific design chosen by the manufacturer.

Chapter 2 of this document provides information needed to understand the rationale for equipment characteristics and requirements stated in the remaining sections. It describes typical equipment operations and operation goals, as envisioned by the members of EUROCAE WG75 (“TCAS”) and RTCA SC 147 (“TCAS”) and establishes the basis for the standards stated in chapters 3 to 8. Chapter 9 contains references.

All CAS are expected to include a computer software package, therefore the guidelines contained in RTCA DO-178C/ EUROCAE ED-12C [1], [2] (*or the most current published revision*) should be considered in addition to DO-254/ ED-80 [3], [4].

Requirements are stated using the word **shall** (*Rm.nn*) followed by chapter number and a number unique within the chapter.

1.2 BACKGROUND

The airborne CAS TCAS has been in service since 1990, during which time it has been the only system that generates Resolution Advisories (RAs). There are other systems that track proximate traffic and provide a variety of displays or alerts but none of these advises the pilot how to avoid collision with a threat aircraft. Now there are new CAS such as Airborne Collision Avoidance System X (ACAS X) and Detect and Avoid (DAA) systems are also being developed to facilitate the entry of Unmanned Aircraft Systems or Remotely Piloted Aircraft into non-segregated airspace. It is essential that these new systems interoperate with the old, and that one family of CAS causes no harm to the operation of any other family of CAS.

The most obvious requirement is that the RAs, generated by the individual CAS on the aircraft in the collision avoidance encounter, are compatible. For example, the developers of TCAS determined that the separate RAs generated on two aircraft in

¹ By default, in this document, the term TCAS is an abbreviation for TCAS II

conflict need to be coordinated, so that if one aircraft is aiming to pass above the other, the other aircraft will aim to pass below the first. At the simplest level, in two-aircraft encounters, TCAS achieves vertical coordination by sending and receiving messages that convey the senses (up or down) of the RA manoeuvres that the two TCAS recommend. More generally, a horizontal RA on one aircraft is usually compatible with a vertical RA on the other aircraft.

The TCAS logic, i.e. the algorithms that determine RAs, has undergone a series of revisions, and each revision has been demonstrated to be interoperable with the preceding versions before final approval. The validation work for these revisions assumed that the RAs on the two aircraft in conflict are coordinated.

An FAA White paper [5] addressed the question of coordination between TCAS or ACAS Xa and other novel airborne collision avoidance systems using vertical RAs. A major conclusion, based on simulations, was that coordination of vertical RAs is essential. Indeed, better overall performance is achieved when the second aircraft in an encounter has no CAS compared to a CAS-equipped aircraft which fails to coordinate its vertical RAs. While this has not been demonstrated for horizontal coordination, simulations during the development of ACAS Xu indicate that effective coordination of horizontal RAs improves collision avoidance between two ACAS Xu systems, and more markedly improves collision avoidance between ACAS Xu and CAS of different design that also generate horizontal RAs [25]. These MASPS require that horizontal RAs be coordinated (R2.1, section 2.2).

The issue of interoperability is broader than coordination alone; although it is essential that RAs are coordinated, it is also certain that more is required for full interoperability, which is why (as mentioned above) it is standard practice to ensure that new versions of TCAS perform well in encounters with previous versions of TCAS. An example of incompatibility between two CAS was provided by an early development version of ACAS Xa and TCAS. It was found in simulations that the rate of RA sense reversals on TCAS when coordinating with this early version of ACAS Xa increased by a factor of 3 and the rate of RAs to cross in altitude increased by a factor of 2. While coordination was perfect and both systems performed well in encounters with like systems, they proved to be incompatible with each other [6]. These effects were judged to be unacceptable and were completely resolved in later development versions of the ACAS Xa logic.

These MASPS provide interoperability provisions between current CAS, CAS under development and future CAS. It also covers interoperability between CAS and DAA.

1.3 SCOPE AND ASSUMPTIONS

1.3.1 Detect and Avoid

These MASPS protect the correct operation of systems that generate RAs for the avoidance of imminent collision.

DAA contains a Remain Well Clear (RWC) function and a collision avoidance function. Some implementations might exclude one of these functions. The DAA collision avoidance function is a CAS and is referred to as CAS in this document. While CAS are the main subject of these MASPS, there are also requirements relating to RWC to ensure full interoperability between CAS on other aircraft and RWC. In the context of this document, DAA is not referenced since it might contain both functions. The document will reference the two functions distinctly as RWC and CAS.

RWC and other systems can interact with CAS, for example: by giving alerting or guidance affecting manoeuvres on a collision avoidance timescale; or by tracking aircraft using active interrogation and reply on 1030/1090 MHz. These MASPS include requirements on these systems to ensure satisfactory performance of CAS. Interoperability between RWC and systems other than CAS, including between RWC of different design, is not addressed.

Determining the extent to which stand-alone RWC and other systems can share the signals and spectrum used by CAS is the responsibility of the appropriate governmental agencies. For example, these MASPS require RWC to monitor ADS-B and 1030/1090 MHz in order to ensure complementary manoeuvre guidance, but these provisions do

not imply permission to use active interrogation on 1030 MHz other than to support a collision avoidance function.

NOTE 1: *TCAS I (DO-197A) has its own interference limiting provisions that differ from those of TCAS II.*

1.3.2 Aircraft Types

These MASPS address systems installed on aircraft that typically operate in managed and unsegregated airspace, in numbers and at densities broadly comparable with those that exist today. They are not intended to facilitate a radical increase in aircraft density nor the widespread operation of novel aircraft types. For example, these MASPS are not intended to provide guidance on collision avoidance systems installed on very small Remotely Piloted Aircraft Systems that are confined to operations close to the surface.

1.3.3 Transponders, Passive CAS and Operational Coordination Messages (OCM)

Much of the functionality discussed in these MASPS will require transponders that comply with DO-260C/ ED-102B and DO-181F/ ED-73F or later [30], [31], [32], [33]. (DO-260C/ ED-102B and DO-181F/ ED-73F will be jointly² referred to as the New Transponder MOPS, and transponders complying with these MOPS will be referred to as New Transponders.) Equipping CAS with such New Transponders is essential to enable the full operation of some CAS (e.g. section 3.5.3.2). However, even the New Transponders will not deliver the full functionality described in these MASPS. This issue is discussed below.

Current CAS are Active CAS that coordinate their RAs by sending Mode S interrogations on 1030 MHz and transponder replies on 1090 MHz. Passive CAS are introduced and discussed in these MASPS. These systems are defined as CAS that do not use active interrogation for surveillance. Surveillance is likely to depend on a variety of devices and approaches, but it is assumed here that they will make full use of ADS-B. It is also assumed they will use ADS-B to coordinate RAs; these MASPS describe the contents and protocols for Operational Coordination Messages (OCMs). However, the New Transponder MOPS do not provide for the broadcast of OCM. The implementation of OCMs is contingent on further work to define their operational requirements, and to confirm that the frequency of OCM transmissions can be contained within the limits considered acceptable.

These MASPS treat Passive CAS as a future concept that has not been reviewed for operational use. These MASPS do not serve the purpose of a MOPS for Passive CAS, nor comparable detailed design documents; the functional, safety and performance requirements for Passive CAS are not addressed.

Provision is made for Passive CAS in these MASPS so that the present generation of CAS, e.g. ACAS Xa and Xu, can include the capability to transmit OCMs and thus coordinate with future Passive CAS. It is understood that Passive CAS could use any of many different schemes to coordinate RAs between themselves; the fact that a scheme based on the use of OCMs is standardised here is not intended to imply the use of a particular link. However, OCMs are likely to be the only method for the present generation of CAS to coordinate RAs with Passive CAS; any coordination mechanisms that are not provided now will result in an inability to coordinate with legacy Active CAS, resulting in limitations in the RAs that future Passive CAS can generate. These MASPS have been designed for 1030/1090 MHz. If other frequencies, e.g. 978 MHz for UAT, are used for exchange of information, all the message exchanges required for coordination need to be assured.

1.3.4 CAS Configurations and Constraints

These MASPS contain requirements governing many different potential CAS configurations. However, just because a configuration is enabled by these MASPS

² While it is assumed that manufacturers will develop transponders complying with these two MOPS jointly, it is possible that transponders will be developed that comply with DO-260C/ ED-102B but not comply with DO-181F/ ED-73F and *vice versa*. This complication is not discussed in these MASPS.

does not mean it will be allowed in any particular airspace. Configurations include whether or not the CAS:

- has 1030/1090 MHz interrogation/reply capability
- can transmit OCMs (specific ADS-B messages that contain the same pairwise RA complements as TCAS Resolution Messages, which are interrogations on 1030 MHz that coordinate RAs),
- can receive OCMs,
- is fitted in conjunction with a Mode S transponder, which might or might not meet the New Transponder MOPS, and
- is “junior”.

NOTE 2: *The concepts of “senior”, “junior” and “peer” are defined in the Glossary (section 1.4), and explained in section 3.5.3.*

Not all these different configurations are permissible. Those that are not permissible include:

- a junior CAS that is not always able to generate horizontal RAs, e.g. a junior ACAS Xa, (see R3.69, section 3.5.3.2)³;
- a junior CAS in conjunction with a transponder not complying with the New Transponder MOPS or later, because it would be unable to announce itself as junior resulting in the rules for coordination breaking down (see R3.20, R3.21, section 3.4.1);
- a transponder or transceiver that will be used for coordinating RAs which has an aircraft address consisting of 24 zeroes or 24 ones (see R3.4, section 3.1); and
- a senior Active CAS that issues only horizontal RAs and lacks the logic to calculate vertical avoidance manoeuvres, resulting in an inability to coordinate vertical RAs with TCAS (see **NOTE 2**).

NOTE 3: *The senior Active CAS will disable the ability of TCAS to reverse its RAs when it has the lower relative aircraft address. To mitigate this hazard, it is required to coordinate vertical RAs with TCAS so that the TCAS RA can be reversed if necessary, (see section 4.6.1.2 and R3.11 and R4.10 in section 4.6.2).*

There are also configurations that, although permissible, would fail to achieve the full functionality described in these MASPS and that can be expected to deliver degraded performance in some circumstances.

- Where it is determined that an Active CAS can be paired with a transponder that does not comply with the New Transponder MOPS, the Active CAS will be indistinguishable from TCAS resulting in inappropriate or incorrect coordination in some circumstances. The consequences are discussed in these MASPS.
- It was noted in section 1.3.3 that failure to field transponders that transmit OCMs would hinder the development of Passive CAS, which will depend on the exchange of OCMs.
- The acceptability of fielding Passive CAS that need to receive an OCM for coordination with Active CAS would need to be demonstrated (see the last two paragraphs of section 3.5.3.2) because of the likelihood of a large population of Active CAS that cannot transmit OCMs. For example, consider an encounter between a Passive CAS that requires OCMs to coordinate and an ACAS Xu that cannot transmit OCMs. In this example, coordination would not be possible; thus, it would not be permissible for the Passive CAS to generate either vertical or horizontal RAs, and CAS protection would be provided solely by the Active CAS.

1.4

GLOSSARY

ACAS – Airborne Collision Avoidance System. An aircraft system based on secondary surveillance radar (SSR) transponder signals which operates independently of ground-

³ R3.69 refers to non-vertical RAs rather than horizontal RAs, thus not precluding (for example) speed change RAs.

based equipment to provide advice to the pilot on potential conflicting aircraft that are equipped with SSR transponders. (ICAO definition).

ACAS II – An ACAS that meets the requirements of the ICAO ACAS II SARPs [9]. ACAS II is defined in the SARPs as an ACAS that generates vertical RAs only. In these MASPS, ACAS II is used when the text refers to both TCAS II and ACAS Xa.

ACAS Xa – The Active CAS standardised in DO-385/ ED-256. ACAS Xa generates vertical RAs only.

ACAS Xu – The Active CAS standardised in DO-386/ ED-275. ACAS Xu generates both vertical and horizontal RAs as well as RWC alerting and guidance.

Active CAS – A CAS that can communicate via 1030/1090 MHz interrogations and replies. An Active CAS is identified by 3-bit CCCB Aircraft CAS Type/Capability values equal to 000, 001, 010, or 011.

Active CAS of Junior Status – A CAS that has active 1030/1090 MHz interrogation/ reply capability but is required by regulatory authorities to perform responsive coordination in encounters with an aircraft reporting 3-bit CCCB Aircraft CAS Type/Capability values equal to 000, 001, or 010.

Active Coordination – The type of coordination used when the two CAS are considered peers and both aircraft have a Mode S transponder and 1030/1090 MHz discrete interrogation/reply capability.

ADS-B Aircraft Operational Status Message – Systems complying with DO-260B/ ED102A support the CA Operational sub-field. Systems complying with DO-260C/ ED102B (see New Transponder MOPS) additionally support the CA Coordination Capability Bits (CCCB) and DAA sub-fields, which are used in these MASPS to determine the coordination protocols to be used between CAS.

ADS-B TCAS RA Broadcast – An ADS-B message containing details of an RA and the identity of a single threat.

Collision Avoidance (CA) – Last-resort directive actions or advisories intended to prevent a collision between two aircraft in an unsafe flight geometry.

CA Coordination Capability Bits (CCCB) – A data sub-field conveyed by ADS-B, but only by systems complying with DO-260C/ ED-102B or later revisions. It defines the coordination characteristics of a CAS, which are used to determine the coordination protocols to be used to exchange coordination messages.

Collision Avoidance System (CAS) – A system for avoiding mid-air collision between aircraft.

CA Operational – A one-bit sub-field of the ADS-B Aircraft Operational Status Message announcing that the transmitting aircraft is equipped with a CAS operating in a mode that can issue RAs.

CAS logic – Collision avoidance logic subsystem within a CAS.

Coordination – The process of ensuring that the collision avoidance systems on any two conflicting aircraft select complementary avoidance RAs.

Coordination Reversal – A reversal of the sense (or intent) made in order to comply with an RA complement in an encounter between two CAS-equipped aircraft. Coordination Reversals are implemented by the slave (or junior) CAS based on information received from the master (or senior) aircraft.

Detect and Avoid (DAA) – An aircraft system that can contain a Remain Well Clear (RWC) function and a collision avoidance function. Some implementations might exclude one of these functions.

In these MASPS, the abbreviation DAA is most frequently used to refer to a data sub-field that defines whether or not the aircraft is equipped with a RWC function.

Explicit Coordination – Coordination in which each aircraft in an encounter uses real-time exchange of information to ensure compatible RAs.

Geometric Reversal – A reversal of the sense (or intent) of an RA made in order to improve the prospects of resolving the threat of collision. In encounters between two CAS-equipped aircraft, only the master (or senior) CAS can initiate a geometric reversal.

Interoperability – The capability of a collision avoidance system or Detect and Avoid system to operate in airspace with other collision avoidance systems without negatively impacting the collision avoidance systems.

Junior – The junior CAS must always ensure that its RA sense is compatible with the RA sense of the senior CAS in responsive coordination.

Manoeuvre – A change in an aircraft's trajectory or speed (a vertical and/or horizontal acceleration) due to aircraft dynamics, pilot intervention, or automatic response.

Master/slave – A method for differentiating peer CAS in Active and Passive Coordination. Master CAS is that on the aircraft that has the lower ICAO address. The master is given priority in coordination tiebreaking and is allowed to initiate geometric reversals.

Modified Active protocol – the set of rules that require a senior CAS to transmit TCAS Resolution Messages to a junior CAS in Responsive Coordination.

Modified Passive protocol – the set of rules that require a senior CAS to transmit OCMs to a junior CAS in Responsive Coordination.

Near Mid-air Collision (NMAC) – Two aircraft coming within 100' vertically and 500' horizontally.

New Transponders – Transponders that comply with DO-260C/ ED-102B and DO-181F/EUROCAE ED-73F.

New Transponder MOPS – DO-260C/ ED-102B and DO-181F/ ED-73F, which, in these MASPS, are discussed as though jointly applicable to the transponder in question.

Operational Coordination Message (OCM) – ADS-B message that contains the same pairwise RA complements as TCAS Resolution Messages. Passive Coordination uses the exchange of OCMs instead of discrete coordination interrogations and replies. OCM is a future concept not supported by systems complying with DO-260C/ ED102B (see New Transponder MOPS).

Passive CAS – A CAS that does not use active interrogation for surveillance.

NOTE: *A CAS that tracks aircraft passively and does not use interrogations for surveillance, but uses TCAS Resolution Messages for coordination, is functionally indistinguishable from an Active CAS of junior status for coordination purposes.*

Passive Coordination – The type of coordination used when the two CAS are considered peers and both aircraft have ADS-B In and Out but no 1030/1090 MHz discrete interrogation/reply capability.

Peer – The CAS on two aircraft in an encounter are considered peers when either CAS is deemed suitable to be the master CAS, in Active or Passive Coordination. In particular, they must have the ability to coordinate in the same way and have equivalent capability to validate the intruder position (via active interrogation or other means).

RA complement – A generic term referring to the VRC and HRC subfields in TCAS Resolution Messages and OCMs that restrict the choice of RA sense by the receiving CAS so that it does not conflict with the RA generated by the CAS sending the message.

Remain Well Clear (RWC) – The ability to detect, analyse and manoeuvre to avoid potential conflicting traffic by applying adjustments to the current flight path in order to prevent the conflict from developing into a collision hazard.

Resolution Advisory (RA) – A recommended collision avoidance manoeuvre to either increase or maintain the miss distance relative to an intruding aircraft. Normally these are indicated to the pilot, but there are contexts in which the logic generates RAs that are not indicated to the pilot; for example, multi-threat encounters where existing designs need to calculate the RA for each threat before identifying a global RA that is identified to the pilot.

Reply Information (RI) – A data field contained in air-air replies (DF0 and DF16) to surveillance interrogations. It plays a central role in determining the protocols to be used when coordinating RAs between Active CAS.

Responsive Coordination – the type of coordination used when the two CAS are not considered peers. One CAS is considered senior and the other junior.

Responsive Protocol – the set of rules used by the junior CAS in Responsive Coordination.

Senior – The senior CAS limits the choice of RAs by the junior CAS in Responsive Coordination, including any need to reverse. It sends coordination messages to the junior CAS using the Modified Active or Modified Passive protocols. These coordination messages ensure the choice of an RA that is compatible with the RA generated by the senior CAS.

Sense – The direction that an RA may take (i.e. either up or down for vertical RAs).

Sense Reversal – A change to the sense opposite that of the existing RA.

Slave – see master/slave.

TA Only Mode – CAS mode in which TAs are displayed and RAs are not generated or displayed.

TA/RA Mode – CAS mode in which both TAs and RAs are issued as specified.

TCAS Broadcast Interrogation Message (TBIM) – A broadcast on 1030 MHz made by Active CAS to enable Active CAS to monitor their density in order to limit the number of interrogations received by transponders from Active CAS.

TCAS II – The legacy Active CAS standardised in DO-185 & ED-143. The unqualified term TCAS is sometimes used to refer to TCAS II in these MASPS.

TCAS Resolution Message – The 1030 MHz message containing the Vertical RA Complement and Horizontal RA Complement. This is defined in DO-185 & ED-143 and their successors.

Threat – An intruder deserving special attention either because of its close proximity to own aircraft or because successive range and altitude measurements indicate that it could be on a collision or near collision course with own aircraft. The warning time provided against a threat is sufficiently small that an RA is justified.

Traffic Alert and Collision Avoidance System (TCAS) – An Active CAS. Unless explicitly stated, all references to TCAS refer to any version of DO-185/ ED-143, TCAS II Minimum Operational Performance Standards (MOPS).

Traffic Advisory (TA) – A display and aural indication given to the flight crew that a certain intruder is a potential threat.

1.5

ABBREVIATIONS

ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance-Broadcast
ATC	Air Traffic Control
CA	Collision Avoidance
CAFÉ	Collision Avoidance Fast Time Emulator
CAS	Collision Avoidance System
CCCB	CA Coordination Capability Bits
CSPO	Closely Spaced Parallel Operations
DAA	Detect and Avoid
DNA	Designated No Alert
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
fpm	feet per minute
HRC	Horizontal RA Complement
ICAO	International Civil Aviation Organization
IFF	Identification Friend or Foe
MASPS	Minimum Aviation System Performance Standards
MHz	Megahertz
MOPS	Minimum Operational Performance Standards
ms	millisecond (10 ⁻³ seconds)

NMAC	Near Mid Air Collision
OCM	Operational Coordination Message
RA	Resolution Advisory
RF	Radio Frequency
RI	Reply Information
RWC	Remain Well Clear
SARPs	(ICAO) Standards and Recommended Practices
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TBIM	TCAS Broadcast Interrogation Messages
UAT	Universal Access Transceiver
VRC	Vertical RA Complement

CHAPTER 2

GOALS FOR AIRBORNE COLLISION AVOIDANCE INTEROPERABILITY

2.1 INTRODUCTION

The requirements contained in this document are intended to ensure interoperability between all CAS and, in the limited aspects described in section 4.3, between CAS and RWC functions, operated in the airspace.

The CA interoperability requirements apply to any equipment that generates RAs to avoid collision, and to other airborne systems, such as RWC systems, that might generate manoeuvre guidance that conflicts with CA RAs.

For this purpose, interoperability is defined as compatibility between CAS and has the following specific goals:

- New CAS entering the airspace must not degrade the performance of existing CAS.
- Existing CAS must not be required to change (e.g. hardware, software, formats) to interoperate with the new CAS.
- To the extent possible, new CAS should not restrict future CAS from taking advantage of technological advances and innovative designs.

The high-level requirements contained in section 2.2 are intentionally broad in order to capture the intent of the generic interoperability requirements without limiting potential approaches to developing interoperable systems. At the time these MASPS were published, TCAS and ACAS Xa were the only CAS that generated RAs; the MOPS for ACAS Xu are contemporary with these MASPS. The only accepted methods to meet the high-level requirements were those used for TCAS and ACAS Xa as described below.

NOTE 1: *While updates to TCAS were designed to interoperate with previous TCAS versions, it is not realistic to expect TCAS to be redesigned to accommodate the requirements of new CAS systems. Therefore, new CAS systems will need to be interoperable with TCAS.*

2.2 HIGH LEVEL INTEROPERABILITY REQUIREMENTS

Coordination of RAs is expected to remain the core enabler of CA interoperability as it ensures the selection of compatible RAs between two disparate systems. Coordination **shall** (R2.1) be used between all potential pairings of aircraft equipment that can normally generate RAs.

NOTE 2: *Coordination requirements vary depending on the capabilities of the two CAS, and the capabilities of the aircraft on which they are installed.*

2.2.1 Coordination Requirements

- 1) Any two systems that generate RAs shall (R2.2) ensure compatible RAs using a standardised coordination protocol.
- 2) The coordination protocols between peer CAS shall (R2.3) be capable of arbitrating incompatible initial RAs and updating subsequent RAs in order to remain compatible.
- 3) The coordination protocols between non-peer CAS shall (R2.4) be capable of selecting compatible RAs and updating subsequent RAs in order to remain compatible.
- 4) In an encounter between non-peer CAS, once the RAs have been coordinated, the junior CAS shall (R2.5) maintain compliance with the most current coordination message received from the senior CAS. This issue is discussed in section 3.5.3.2.
- 5) All CAS shall (R2.6) have the capability to select the coordination protocol that is appropriate for use with each potential intruder. This is discussed in section 3.5.

- 6) All CAS and standalone RWC systems shall (R2.7) provide information for the determination and use of the appropriate coordination protocols. This is discussed in section 3.4.1.
- 7) All CAS shall (R2.8) coordinate their RAs in a manner that interoperates with pre-existing CAS such as TCAS and ACAS Xa.

NOTE 3: *The only coordination messages understood by TCAS and ACAS Xa are those that use the field structures and data formats defined for the TCAS Resolution Message in the TCAS MOPS (DO-185B, 2.2.3.9.3.2.4.1).*

NOTE 4: *Currently, the field used for vertical advisories (VRC) has four possible values of which one is 'not assigned', and the field for horizontal advisories has eight possible values of which three are 'not assigned'. Future systems could take advantage of these unassigned bits (for example, to coordinate speed change RAs), but bits that are currently unassigned will be ignored by legacy CAS.*

NOTE 5: *The interpretation of the data contained in these coordination messages is discussed in section 3.2 for vertical advisories and section 3.3 for horizontal advisories.*

Coordination is key to the performance and acceptability of individual CAS. However, coordination alone is not sufficient to ensure the interoperability of two CAS. CA efficacy on the own aircraft is influenced by the behaviour of the CAS on the intruder. Chapter 7 contains requirements relating to the interoperability of distinct CAS logic designs.

2.2.1.1

Coordination Link Requirements

This section considers the requirements that need to be placed on the mechanisms used to coordinate RAs.

Early work on TCAS established the criticality of the RF messages used to exchange coordination information. Coordination increases the chances of successful avoidance of collision, and in some circumstances taking uncoordinated avoiding action actually increases the risk of collision [5]. However, coordination means that the messages sent by one CAS interact with and can modify the operation of CAS on other aircraft. Thus coordination has to be extremely reliable and convey data with high integrity because a message that results in the other aircraft taking the wrong action, i.e. a manoeuvre that thwarts the avoidance action of own aircraft, creates a collision hazard for the other aircraft (as well as own aircraft).

The following requirements ensure that the objective that the aircraft in an encounter avoid collision cooperatively is met.

- 1) Coordination messages shall (R2.9) convey the dimension and sense in which own aircraft is seeking to avoid collision with the aircraft to which the coordination message is addressed. For examples: a) own aircraft will pass above the threat so the threat should pass below own aircraft; b) own aircraft is overtaking the threat intending to pass on its right (at closest approach), so the threat must not turn right; and c) the two aircraft will be head on at closest approach and own aircraft intends to pass to the right of the threat, so the threat must pass to the right of own aircraft.

NOTE 6: *The coordination messages might not convey the sense in which own aircraft intends immediately to manoeuvre, because there are circumstances in which CAS will issue RAs that seem contrary to the coordination message. This can arise in multi-threat encounters where own aircraft must first manoeuvre in one direction to avoid the most urgent threat and later manoeuvre in the opposite direction to avoid a less urgent threat; in this case the resolution message sent to the less urgent threat describes the way in which own aircraft will pass that threat. It also arises when TCAS first issues a climb or descend RA and then an RA to level off, which is a manoeuvre towards the threat, without changing its coordination message.*

- 2) Coordination messages shall (R2.10) identify both own aircraft and the aircraft to which the message is addressed.

- 3) Data sent in coordination messages is an integral part of the CAS logic. Derivation and encoding of the data shall (R2.11) have the same level of assurance as is applied to the CAS logic.
- 4) The data in coordination messages, specifically the VRC or HRC, shall (R2.12) be conveyed with a level of integrity such that the risk of corruption during transmission is negligible.

NOTE 7: *TCAS Resolution Messages are conveyed by Mode S interrogations on 1030 MHz. This automatically provides parity protection that is sufficient for most applications of Mode S data exchange. Nevertheless, additional parity protection is provided to ensure the integrity of the VRC and HRC subfields.*

- 5) Coordination messages **shall** (R2.13) be conveyed in a manner and on a link that ensures that the risk of failure to receive the message is negligible.

NOTE 8: *TCAS Resolution Messages are transmitted at full power regardless of the need to limit interference on the 1030/1090 MHz spectrum, and the transmissions are repeated between six to twelve times within 100 ms in any cycle unless receipt is acknowledged.*

TCAS Resolution Messages are the established means to coordinate RAs and might be considered to set the standard for any alternative. Nevertheless, other RF messages could be used provided they meet the requirements above. It is acknowledged that legacy systems, e.g. TCAS, will be unable to receive and process coordination messages other than TCAS Resolution Messages. This problem is addressed elsewhere in these MASPS. The alternative considered in these MASPS is OCMs. Prior to the use of OCMs, their ability to meet the requirements above needs to be confirmed. Likewise any other mechanism that might be proposed for coordination would have to confirm their ability to meet the requirements above.

If a CAS uses frequencies other than 1030/1090 MHz for message exchange, the CAS **shall** (R2.14) ensure that all the message exchanges required in these MASPS can occur with all approved CAS.

At the time of writing it is difficult to see how to coordinate with all CAS without using 1030/1090 MHz message exchange.

- The active coordination protocol, by its definition, requires interrogation on 1030 MHz and reply on 1090 MHz; no other link is permitted.
- The responsive coordination protocol relies on the present generation of CAS transmitting coordination information, and the present generation of CAS transmits coordination information on only 1030 MHz or 1090 MHz. Thus, in order to perform the responsive coordination protocol, R5.4 requires juniors to transmit their CA capability on 1090 MHz, and R5.5 requires juniors to receive coordination information from seniors on either 1030 MHz or 1090 MHz.
- The passive coordination protocol allows Passive CAS to use any link to coordinate RAs between themselves. In an airspace with multiple coordination links in use, a subset of CAS could use a link that is particular to that subset, provided that all members of that subset can coordinate on different links with all other CAS.

2.2.2 Non-Coordination Requirements

The requirements stated in this section concern spectrum and CAS logic issues and assume that the two CAS can coordinate and do so effectively.

- 1) The combined safety performance of two coordinated CAS shall (R2.15) exceed the safety performance of each individual CAS against an unequipped⁴ intruder in otherwise identical encounters. The safety performance is to be the calculated

⁴ Within these MASPS, unless otherwise specified, the word 'equipped' means CAS-equipped, and the word 'unequipped' means not equipped with CAS.

NMAC rate in a comprehensive and representative collection of simulated encounters (see Chapter 7).

- 2) The use of the 1030/1090 MHz SSR spectrum shall (R2.16) not materially degrade the performance of other users of the same frequencies.
- 3) The use of Mode S messages shall (R2.17) not degrade the surveillance performance of other users of the same messages. For example the use of TCAS Broadcast Interrogation Messages (TBIM) can degrade surveillance performance [7], [8], [9]; see section 6.3.
- 4) The ability to reverse RA sense when the current RA is failing has been found to be essential for CAS. The CAS RA logic shall (R2.18) include the ability to reverse the sense of an RA in extremis, and to do so independently in each dimension that the CAS uses for avoidance action. This requirement applies whether or not the threat aircraft is equipped with a CAS. Where both aircraft are equipped and own CAS is the slave, the slave shall (R2.19) have the ability to reverse the sense of its RAs until and unless it has received a coordination message from the master. Any coordination messages received from the master shall (R2.20) override the slave's choice of RA sense and thus prevent reversals of sense by the slave on its own initiative.

NOTE 9: *An inability to reverse RAs when the other aircraft in an encounter has not sent a coordination message can damage the performance of own CAS. This is primarily a performance issue, but it is also an interoperability issue. Section 4.6 discusses the issues that arise because TCAS does not satisfy R2.19 when the threat is equipped with Active CAS and is the master.*

Reversals of the sense of RAs are rare and should be minimised during the design process.

CHAPTER 3

COORDINATION PROTOCOLS AND THE TRANSMISSION OF COORDINATION INFORMATION

3.1 INTRODUCTION

Coordination, as used in these MASPS, is defined as the process of ensuring that the CAS on any two conflicting aircraft select complementary RAs.

For coordination of RAs, CAS **shall** (R3.1) use Explicit Coordination, meaning that the two aircraft select RAs based on a real-time exchange of coordination messages.

NOTE 1: *The primary coordination information exchanged is in the form of a complement; e.g. for vertical RAs, a Vertical RA Complement (VRC) is exchanged, conveying either “Do not pass above” or “Do not pass below.” Similarly, for horizontal RAs the coordination information is in the form of a Horizontal RA Complement (HRC) that includes an instruction either “Do not turn right” or “Do not turn left”. A CAS receiving a VRC or HRC will restrict its choice of RA sense according to the requirements in section 3.2.*

NOTE 2: *The exchange can be in both directions, as in Active Coordination (3.5.1) and Passive Coordination (3.5.2); or in one direction, i.e. from a senior CAS to a junior CAS, as in Responsive Coordination (3.5.3).*

Coordination messages constrain the choice of RA on the aircraft to which they are sent (the threat), potentially requiring the threat to select an RA that would not have been its own choice. They are sent to ensure that any action by the threat is compatible with the action taken by the pilot following an RA displayed for own aircraft. It follows that the sending of a coordination message implies that an RA is displayed on own aircraft. Coordination messages **shall** (R3.2) correspond to an RA displayed to the pilot of own aircraft except in special cases standardised in section 4.6, which discusses the inability of TCAS to reverse an RA in encounters with an Active CAS-equipped aircraft.

Explicit coordination is a pairwise agreement between two aircraft providing manoeuvres to avoid collision with each other. Thus, the coordination messages must convey the identity of the aircraft sending the message and the identity of the receiving aircraft. The equipment **shall** (R3.3) use a valid ICAO 24-bit address (to ensure its address is unique and not all zeros nor all ones) in all message exchanges with other aircraft. Some links (e.g. UAT) allow for the generation of a random 24-bit address that is not an assigned 24-bit ICAO address. Failure to use an assigned ICAO address increases the risk of duplicate addresses, resulting in a failure to coordinate in every coordination protocol defined in section 3.5.

Since coordination of RAs is essential and requires each aircraft to have a unique address, CAS **shall** (R3.4) disable the generation of RAs if the address of the transponder or transceiving device that will be used for coordination consists of all zeroes or all ones.

In a single threat encounter, if a purely horizontal RA is displayed for own aircraft, own CAS **shall** (R3.5) send an HRC and set the VRC subfield to zero. If a purely vertical RA is generated, own CAS **shall** (R3.6) send a VRC and set the HRC subfield to zero. If a blended RA is generated, requiring both vertical and horizontal avoidance action, both a VRC and an HRC **shall** (R3.7) be sent to the threat. In a multi-threat encounter the coordination messages **shall** (R3.8) be specific to each threat and reflect the avoidance action required for that single threat.

NOTE 3: *Coordination messages do not necessarily contain information on the direction own aircraft should move.*

The objective of the coordination messages is to ensure that the two CAS work cooperatively to achieve an agreed mutual disposition as they pass each other, at closest approach. However, there are cases where the RA presented to the pilot appears to work against that objective. In both TCAS II and ACAS X, the RA in a multi-threat encounter might be to climb even when the VRC sent to one of the threats says “do not pass below” (suggesting that own aircraft might descend), because the most urgent threat requires the climb. Again, in both TCAS II and ACAS X, CAS can first

issue a climb RA and subsequently instruct the pilot to level-off, a downwards manoeuvre towards the threat, in order to limit the operational disruption of a large deviation from clearance.

NOTE 4: *Coordination is a pair-wise process and, in all cases, it is most desirable that the coordination messages sent to each threat are determined by the RA that would be selected for that threat were it a single threat. In a multi-threat encounter, CAS might display an RA to the pilot that does not correspond to an RA that would be selected against one or more of the individual threats. Two examples are given.*

Example a) The RA announced to the pilot might be blended whereas the RA that would be selected against a particular threat is purely horizontal. In this example, a VRC should not be sent to the threat.

Example b) The RA announced to the pilot might be 'climb' whereas the RA selected against a particular threat is 'do not climb'. Here, it is usually not necessary to reverse the sense of a VRC that has been sent to the threat, because the RA displayed to the pilot is likely to be a short-term compromise as discussed below.

Multi-threat coordination: In a multi-threat situation, a CAS **shall** (R3.9) coordinate with each equipped threat individually. The coordination process is referred to as a pair-wise process. This means that when a CAS has declared two or more CAS-equipped intruders to be threats simultaneously, the own aircraft CAS will coordinate with each intruder in turn individually. For example, consider an encounter in which the own aircraft CAS is between two intruders vertically. Here, the own aircraft CAS is likely to select a climb sense against the lower-altitude intruder and a descend sense against the higher-altitude intruder, causing the own aircraft CAS to send a 'do not pass above' VRC to the lower-altitude intruder and a 'do not pass below' VRC to the higher-altitude intruder. In this case, the own aircraft multi-threat logic will combine its two selected senses (climb and descend) into a composite RA (e.g. some form of limit climb/limit descend) for display to the pilot.

In an encounter involving three ACAS II⁵ equipped aircraft in which each recognises the other two as threats and attempts to resolve the encounter using a vertical RA, at least one aircraft will receive conflicting RA complements, and thus be required to pass above one and below the other. Optimising the vertical miss distance from both threats will typically involve some limited movement in a sense that might appear contrary to one of the VRCs. For example, in these specific encounters, it is permitted for ACAS II to issue a climb RA temporarily when a VRC commanding 'do not pass above' has been received, provided that the own aircraft passes below the relevant threat at closest point of approach with a safe vertical miss distance.

NOTE 5: *The requirement to pass above (below) a threat to whom the message "do not pass above (below)" has been sent is a requirement on the outcome. For ACAS Xa, it was found in simulations that violations of this requirement, which might be called Coordination Intent Violations, are even less frequent than NMAs.*

NOTE 6: *This problem does not necessarily exist when the three aircraft attempt to resolve the encounter using horizontal RAs. For example, they can all rotate in a clockwise direction about some central point (that is probably moving with the three aircraft). Such a clockwise resolution would not necessarily mean the three aircraft all turn to the left: a slower aircraft that is being overtaken might need to turn to the right.*

In very rare geometries, in multi-threat encounters it is possible to enter a lock-up condition where all the aircraft receive contradictory RA complements. For example, all aircraft are level and their CAS have both 'do not pass above' and 'do not pass below' VRCs and compliance with both VRCs requires level flight. The CAS logic **shall** (R3.10) be able to overcome lock-up conditions in which all aircraft are required to not pass

⁵ The discussion is based on detailed knowledge of the way the existing systems TCAS and ACAS Xa work. It applies to any CAS issuing vertical advisories only.

above one threat and not pass below another threat. For example, ACAS Xa can identify this situation and breaks it by selecting a positive manoeuvre (climb or descend), which temporarily defers compliance with one of the contradictory VRCs.

3.2

VERTICAL RA COORDINATION

This section and section 3.3 discuss the selection of an RA in encounters with coordinated CAS. In these two sections, the considerations are the same for the senior/junior CAS in Responsive Coordination (see section 3.5.3) as they are for the master/slave in Active and Passive Coordination. Thus, the words ‘master’ and ‘slave’ as used in the narrative text (and notes), include ‘senior’ and ‘junior’ in Responsive Coordination. However, requirements are stated twice: when the requirement is on a slave CAS; and separately, for Responsive Coordination, when the requirement is on a junior CAS.

Coordination is a pair-wise process in which VRC expresses a contract between the two CAS determining which aircraft passes above the other and which below.

Coordination of vertical RAs is achieved by exchange of Vertical RA Complements (VRCs) between CAS, and a resulting choice of complementary RAs on the two aircraft. The VRC is a 2-bit field that is coded thus:

- 0. = No Vertical RA Complement sent
- 1. = “Don’t descend” or “Do not pass below”
- 2. = “Don’t climb” or “Do not pass above”
- 3. = Not assigned

NOTE 7: *“Don’t descend” and “Don’t climb” are the interpretations given in the TCAS MOPS. “Do not pass below” and “Do not pass above” are the interpretations given in the ICAO SARPs [9] for ACAS II and the ACAS Xa MOPS. As explained below, neither interpretation conveys the whole truth.*

The RAs generated by the slave CAS **shall** (R3.11) be designed such that, at closest approach, the vertical disposition of the two aircraft is in accordance with the received VRC.

During Responsive Coordination, the RAs generated by the junior CAS **shall** (R3.12) be designed such that, at closest approach, the vertical disposition of the two aircraft is in accordance with the received VRC.

In two-aircraft encounters involving CAS that are peers, the RA generated by the slave CAS **shall** (R3.13) not cause the aircraft equipped with the slave CAS to manoeuvre downwards when received VRC = 1 or upwards when received VRC = 2. In other words, if the master has an up sense RA, the slave must have a down sense RA.

During Responsive Coordination, in two-aircraft encounters the junior CAS **shall** not (R3.14) issue RAs to manoeuvre downwards when VRC = 1 or upwards when VRC = 2. In other words, if the senior has an up sense RA, the junior must have a down sense RA.

However, VRCs for which the TCAS MOPS definition is “don’t climb” (“don’t descend”) do not necessarily imply that an aircraft that is climbing (descending) at the time the VRC is received needs to level-off, even if the aircraft is equipped with the slave CAS. The RA could be “Monitor vertical speed”, coupled with visual guidance that defines prohibited vertical rates.

Multi-threat encounters present particular problems, which are described in section 3.1. To avoid a collision with the most urgent threat, it could be necessary to generate an RA (as displayed to the pilot⁶) that causes the aircraft to manoeuvre contrary to the VRC received from a less urgent threat. This does not remove the obligation to provide safe vertical separation from the less urgent threat and to pass with the vertical disposition implied by the applicable VRC. The master CAS might subsequently reverse the sense of the VRC.

⁶ ACAS Xa generates a preferred RA for each separate threat before selecting the single (or “global”) RA displayed to the pilot.